How Might the Thermosphere and Ionosphere React to an Extreme Space Weather Event?

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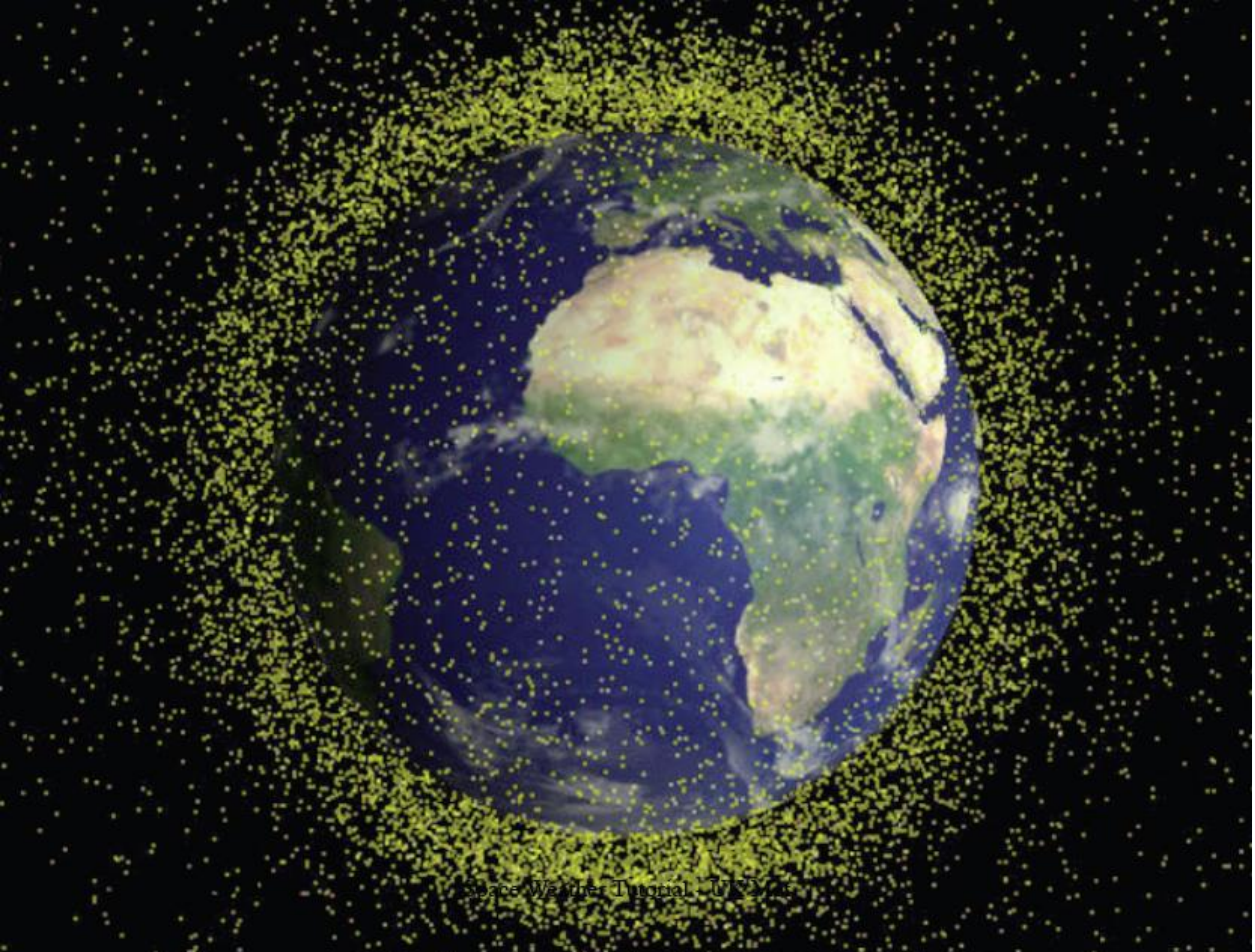
Thermosphere-ionosphere impacts on operational systems

Neutral density and winds for changes in drag on satellites in LEO for orbit prediction, collision avoidance, satellite lifetimes, etc.

- Driven by neutral atmosphere heating, thermal expansion, in-track and cross-track winds, neutral composition, NO cooling, wave propagation (TIDs)

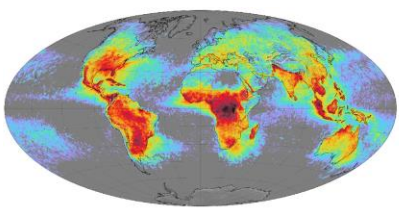
Ionosphere plasma density affects communications, navigation, positioning, timing, which impacts a range of industries: commercial aviation, maritime, surveying, agriculture, etc.

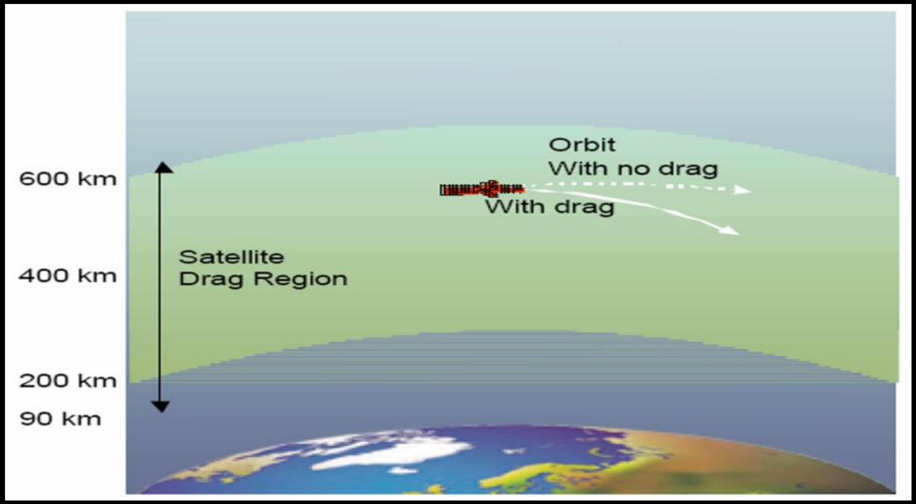
- Driven by expansion of polar cap and magnetospheric convection, plasmasphere erosion, auroral ionization, penetration electric fields to low latitudes, dynamo electric fields, and interaction with the neutral atmosphere winds and composition,



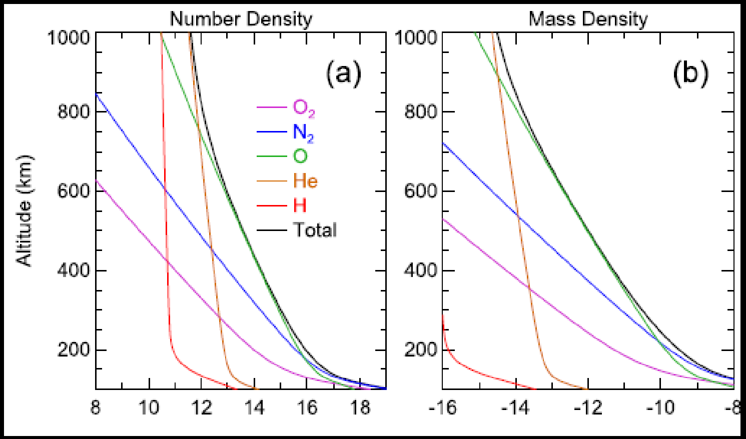
Thermosphere-Ionosphere Drivers: which ones create extreme space weather?

- Solar EUV (1-100 nm): a period of large increase for several days – heats and expands atmosphere increasing drag, enhances plasma density and delays radio signals, possible steeper gradients and stronger irregularities
- Solar flares – intense X-rays ionize D-region causing absorption of radio waves, heating from EUV component
- CME – Carrington-type geomagnetic storms
- Lower atmosphere – tropical convection, tornados, hurricanes, SSW, etc. all drive space weather - but unlikely to drive extreme space weather

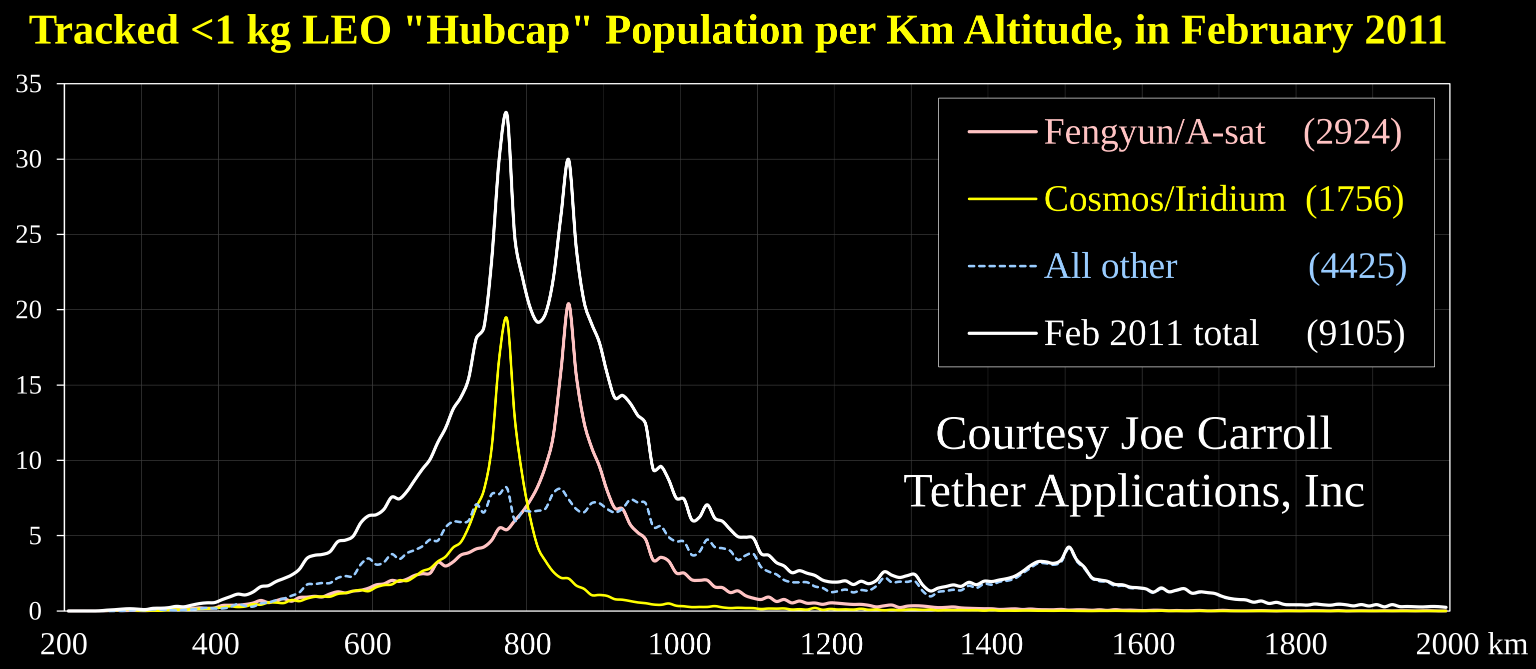




Hotter more expanded atmosphere – drag significant up to 1000 km altitude



Tracked fragments (<1 kg) from <u>two</u> recent collisions are half of all tracked fragments



Satellite drag and collision avoidance

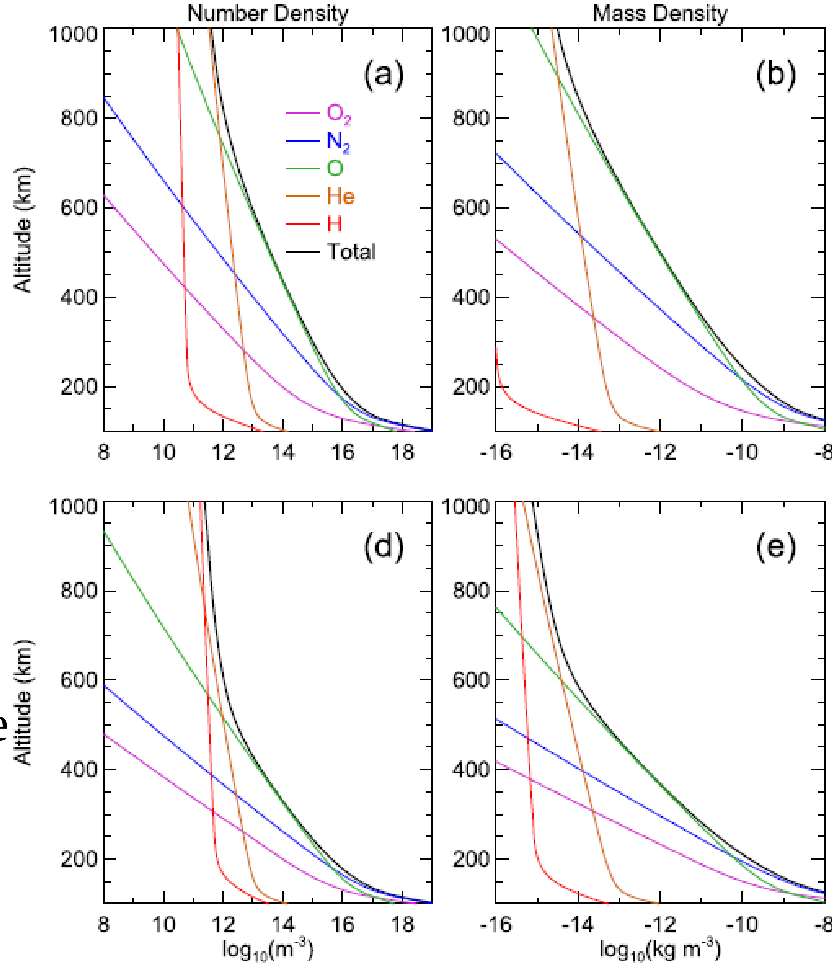
Two distinct risks to operational spacecraft:

1. Direct effect of enhanced drag on the spacecraft, changing its orbit, increases the uncertainty of its position, and reducing the orbital lifetime.
2. Indirect effect of atmospheric expansion on the ability to monitor the trajectories of debris, including objects with high area-to-mass ratio, for collision avoidance.

Neutral winds (in-track and cross-track) - effective density proportional to V^2

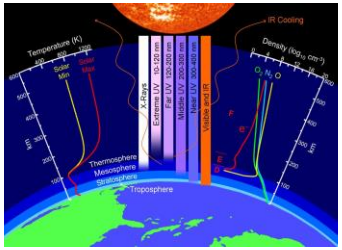
Plasma density at ~800-1000 km altitude becomes a significant fraction of total mass density (~10%)

Structure – important for debris with high area-to-mass ratio and collision avoidance

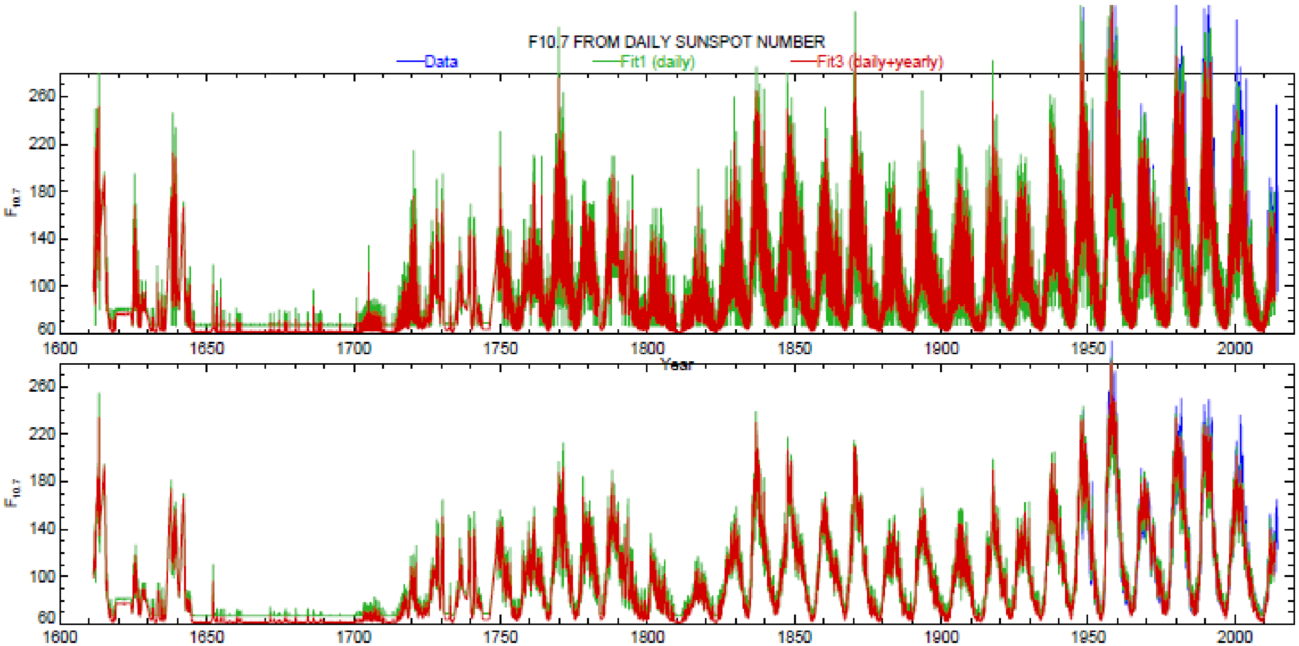


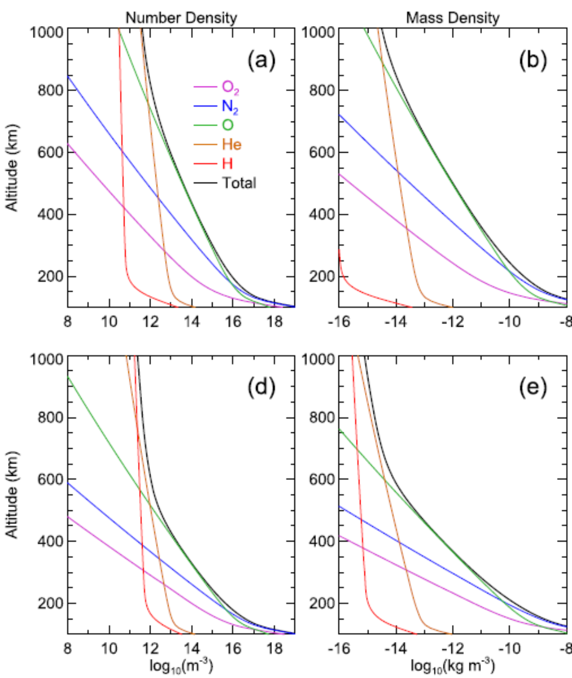
Global mean neutral composition and density profiles at solar min (lower panels) and solar maximum (upper panels) Emmert (2015)

Solar EUV



Empirical neutral density models (e.g., NRLMSISE-00 or Jacchia-Bowman 2008), typically use solar proxies for UV and EUV flux, e.g., based on average of daily and 81-day mean of the 10.7cm solar flux

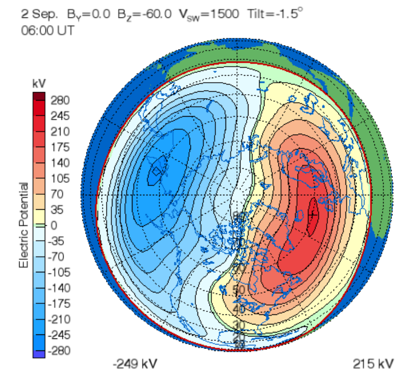


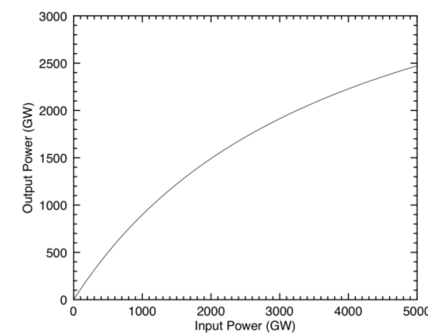


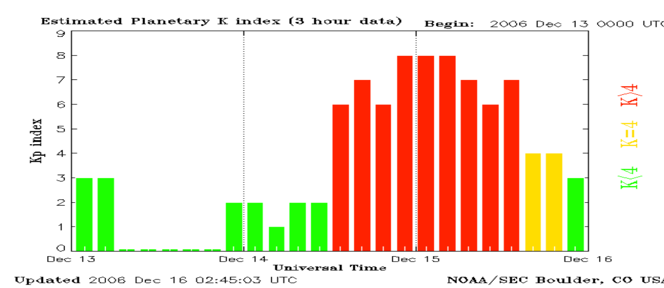
An increase in solar EUV expected for a 100-year event would increase neutral density by 100% at 400 km and by 200% at 850 km increasing drag, and decreasing satellite lifetimes (and removing debris)

Methodology for Geomagnetic Storm Response

- Extrapolate Weimer (2005) magnetospheric convection model for Carrington or July 2012 event solar wind parameters (B_z ~ -60, V_{sw}~2000 km/s, ρ_{sw}~60 cm^{-3})
- Predicts Joule heating power of ~10,000 GW
- Estimate of likely magnetospheric saturation based on past neutral density response to Bastille or Halloween-like storms – reduces Joule heating to ~6,000 GW
- Use Joule heating rates to drive a physics-based thermosphere model for storm with 12-hour duration
- Scale the time-history of a real storm to Carrington magnitude







Coupled Thermosphere Ionosphere Plasmasphere Electrodynamics Model (CTIPe)

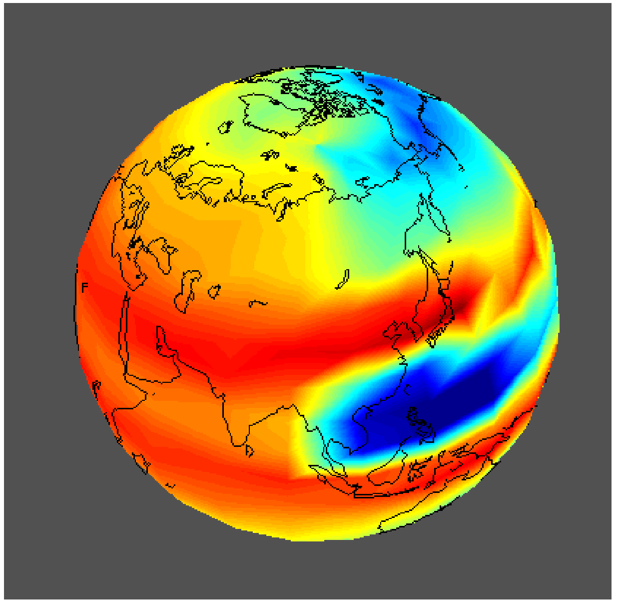
• Global thermosphere 80 - 500 km, solves momentum, energy, composition, etc. Vx, Vy, Vz, Tn, O, O2, N2, … Neutral winds, temperatures and compositions are solved self consistently with the ionosphere (Fuller-Rowell and Rees, 1980);

• High latitude ionosphere 80 -10,000 km, solves continuity, momentum, energy, etc. O^+, H^+, O_2^+, NO^+, N_2^+, N^+, V_i, T_i, …. (open flux tubes) (Quegan et al., 1982;

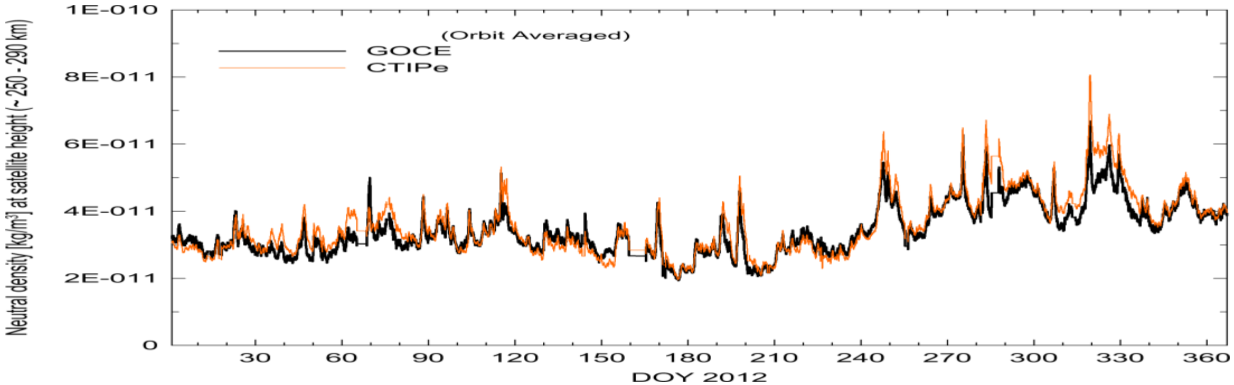
• Plasmasphere, and mid and low latitude ionosphere, closed flux tubes to allow for plasma to be transported between hemispheres (Millward et al., 1996) ;

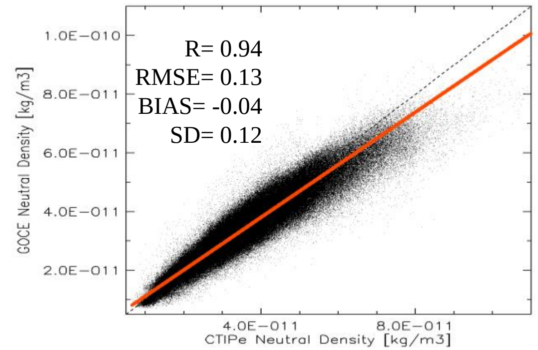
• Self-consistent electrodynamics (electrodynamics at mid and low latitudes is solved using conductivities from the ionospheric model and neutral winds from the neutral atmosphere code) (Richmond et al.,);

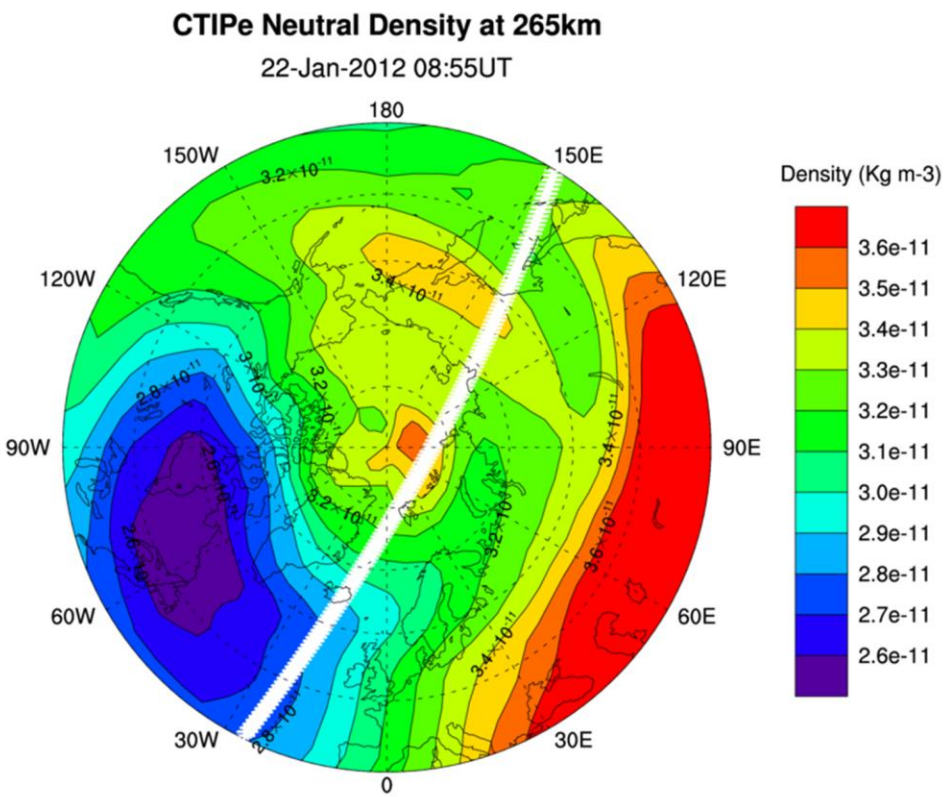
• Forcing: solar UV and EUV, Weimer electric field, TIROS/NOAA auroral precipitation,WAM tidal forcing.

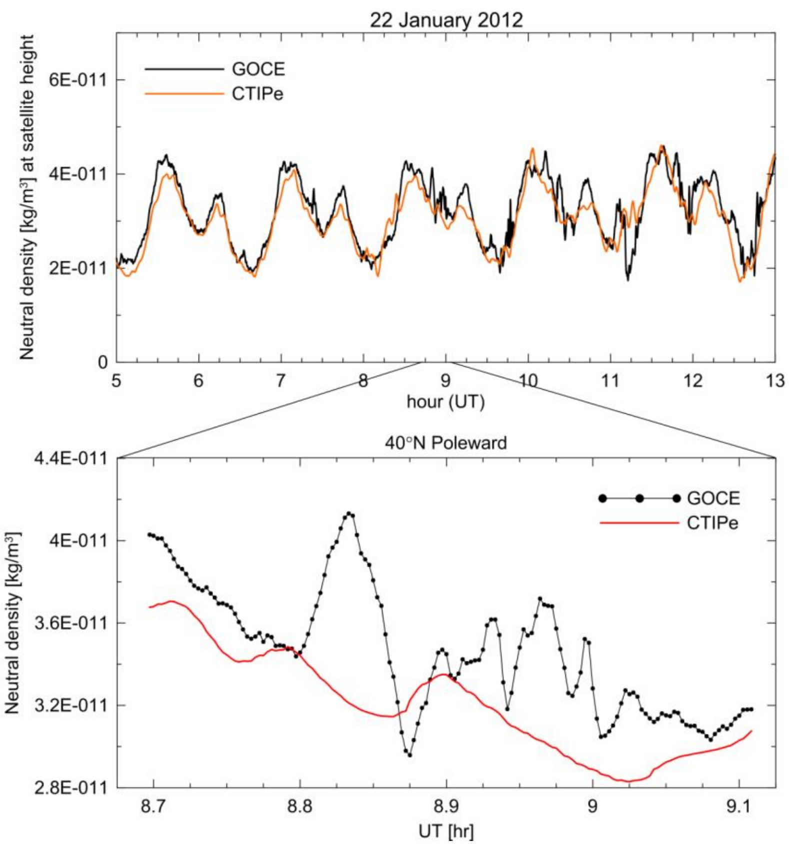


CTIPe vs GOCE quiet

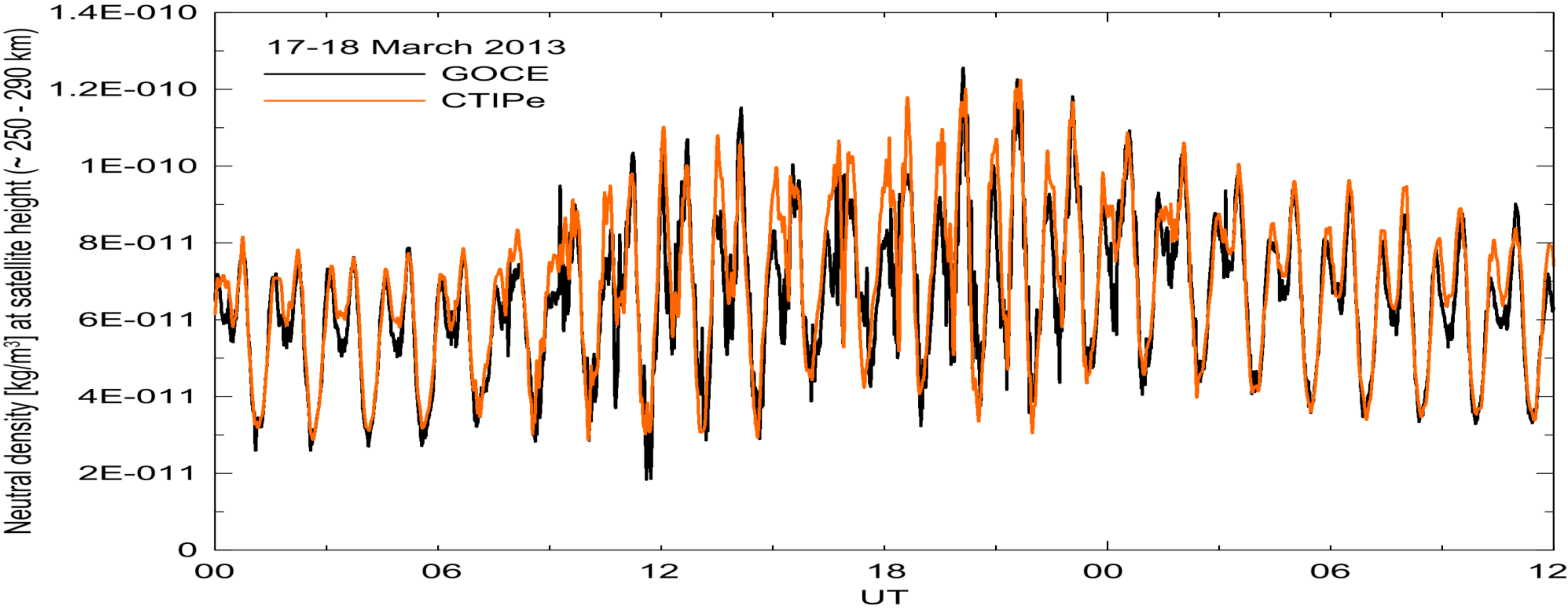




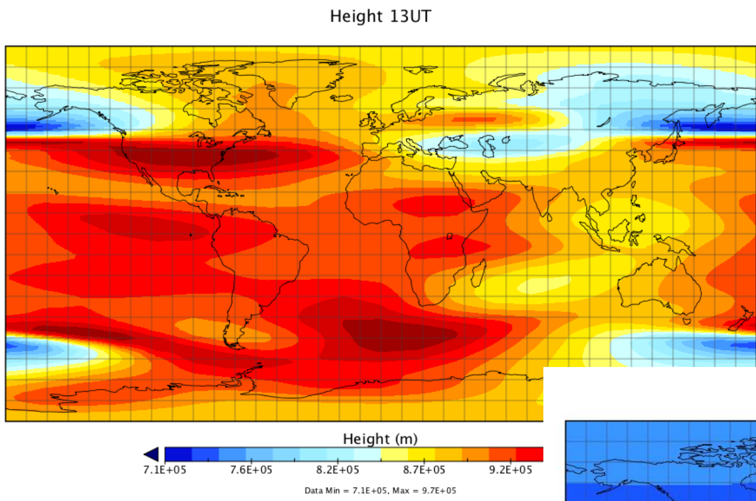




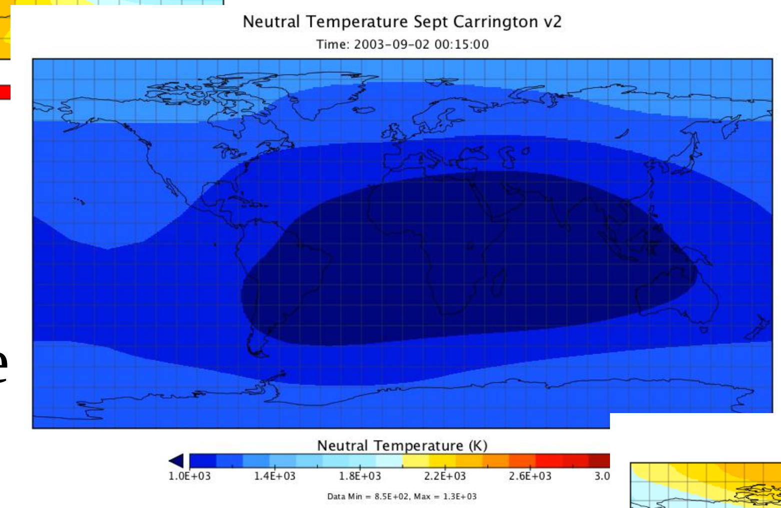
St. Patrick's Day Storm
CTIPe vs GOCE



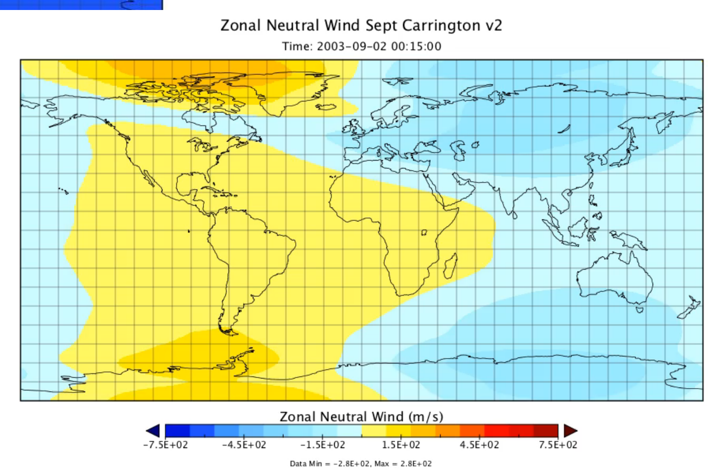
Neutral atmosphere response to Carrington event



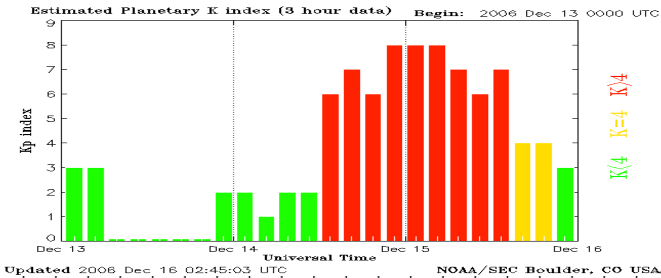
Top of model rises from 500 to ~1000 km, density at 400 km increases by 3 or 4 times a Bastille Day storm response



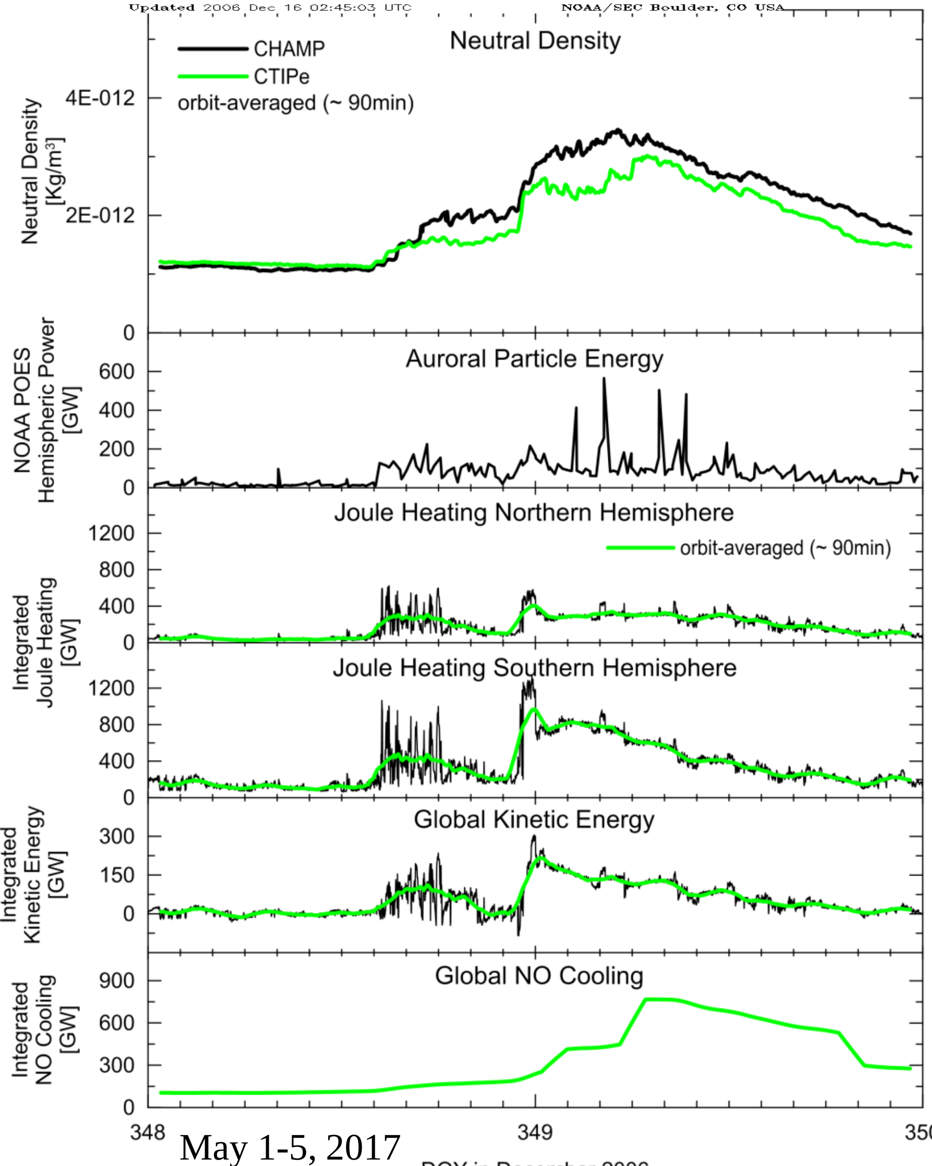
Peak temperature exceeds 3000 K

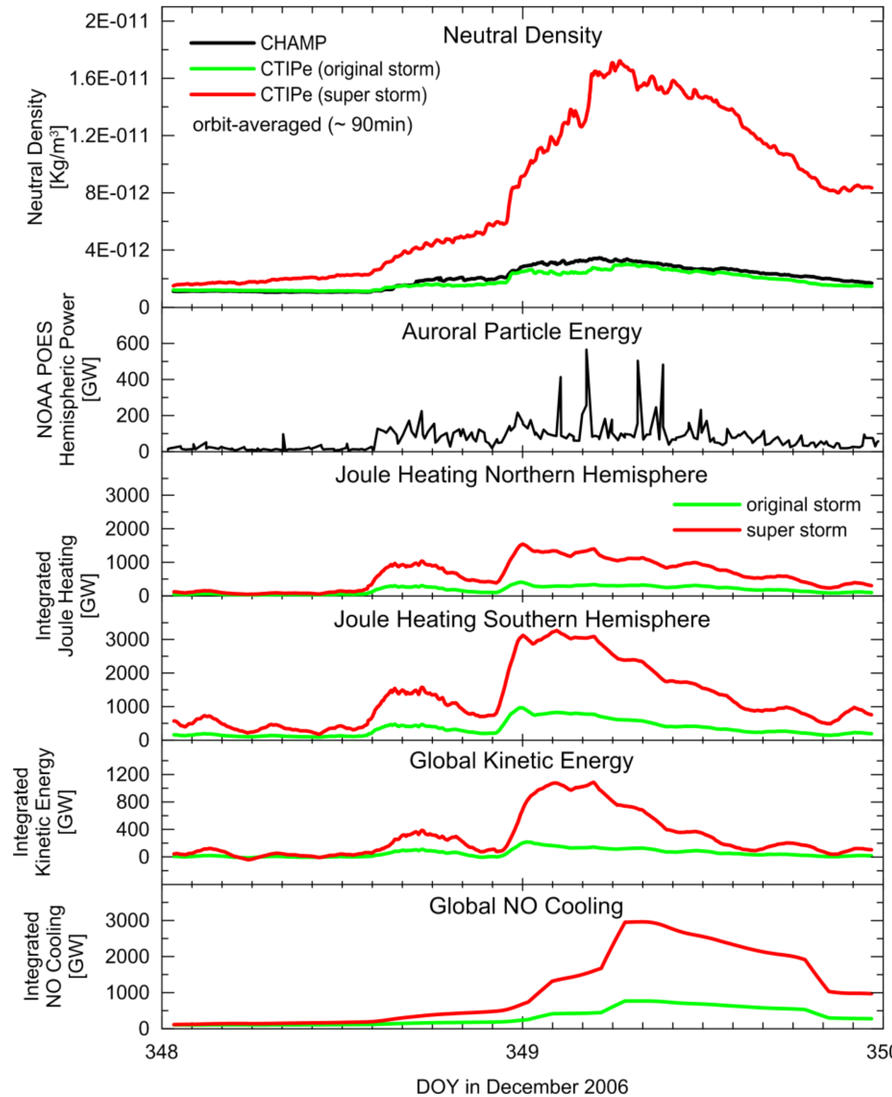


Neutral winds exceed 2000 m/s

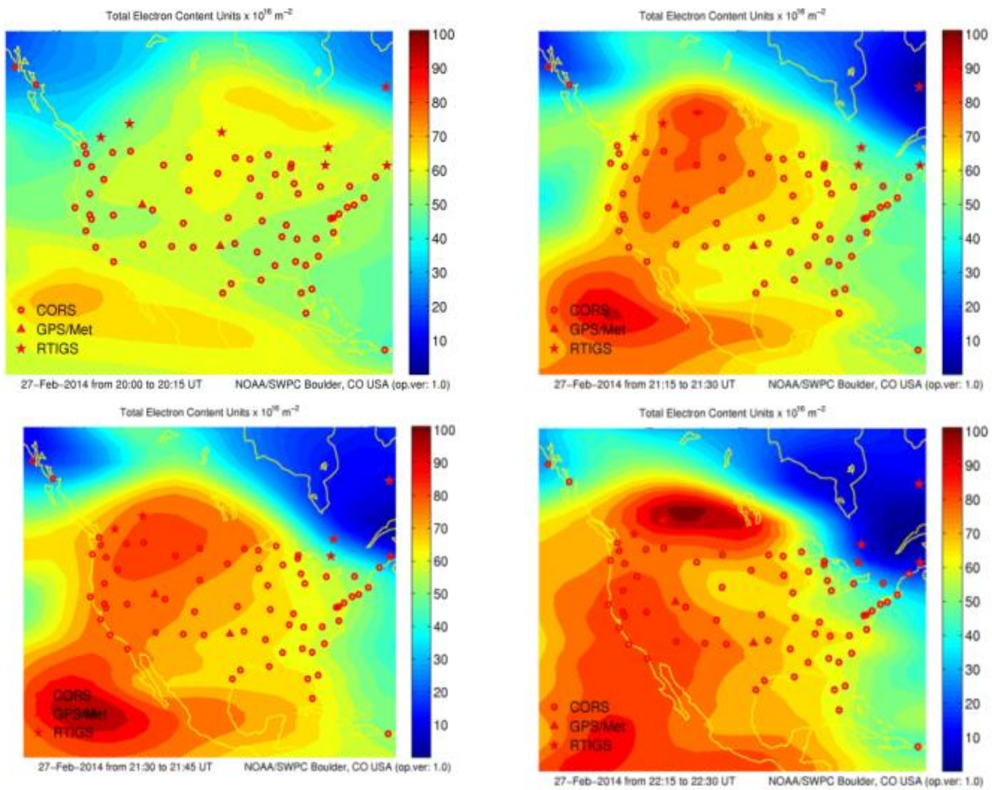


Energy input and density response to realistic time series scaled to peak JH

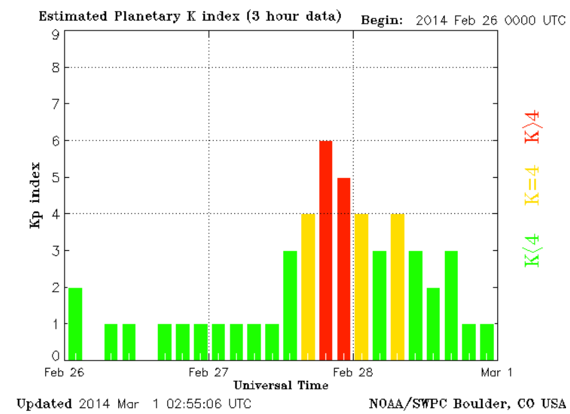


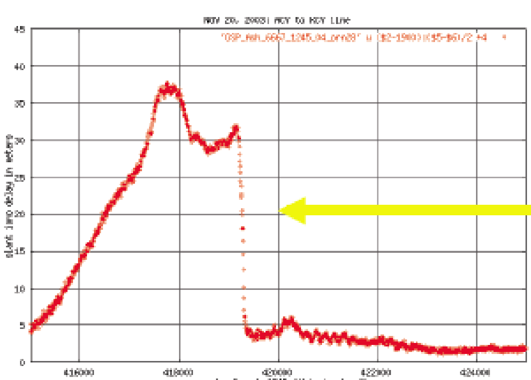


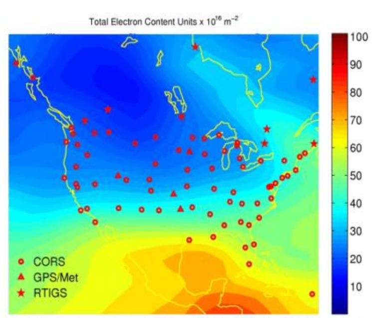
TEC response to expansion of magnetosphere convection



Response of SWPC US-TEC product to modest storm on Feb 27th 2014



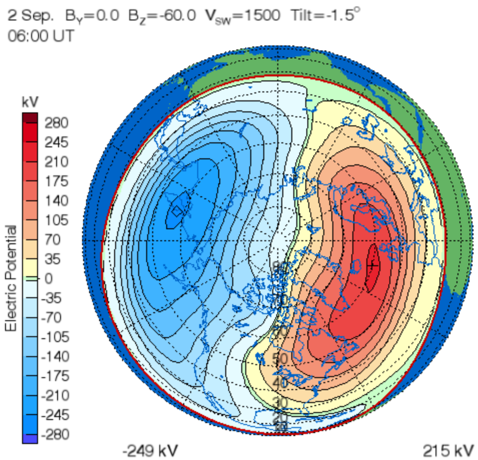


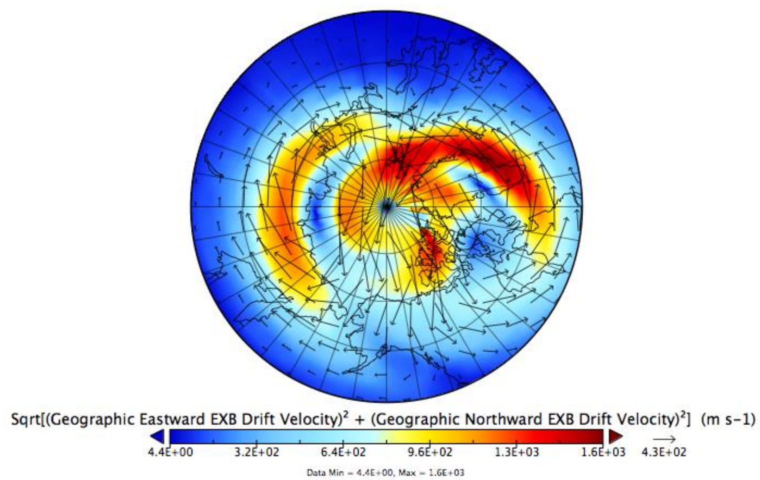


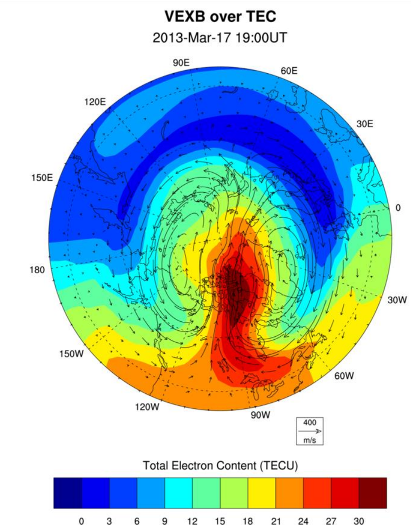
Walls of TEC: compromises integrity of WAAS aviation navigation, 130 TEC units over 50 km, causes 20 meters of delay of GPS signals

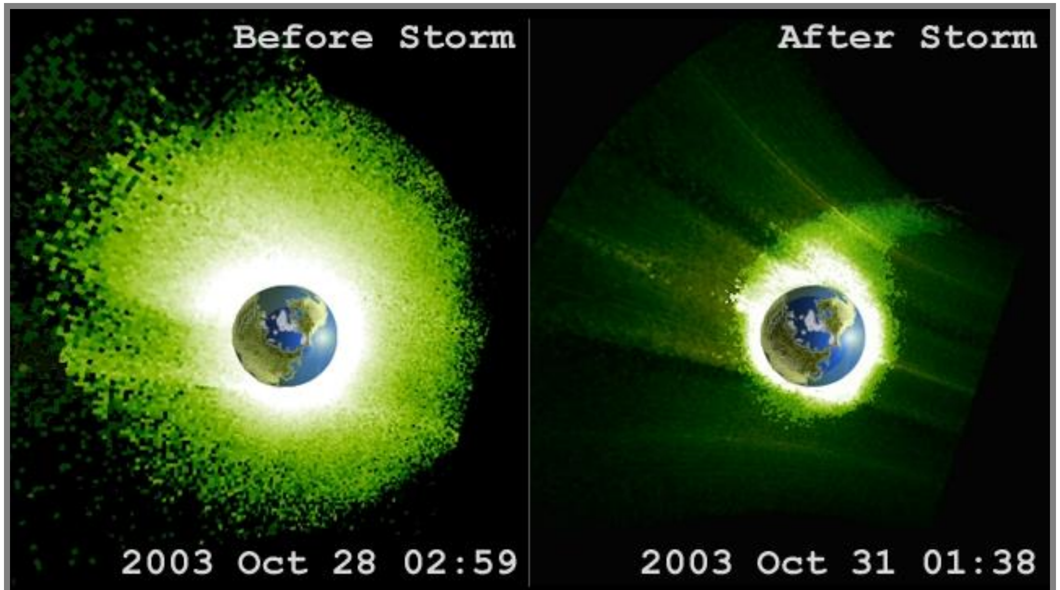
Plasmasphere erosion

Combination of equatorward expansion of polar cap (open/closed field line boundary) and magnetospheric convection





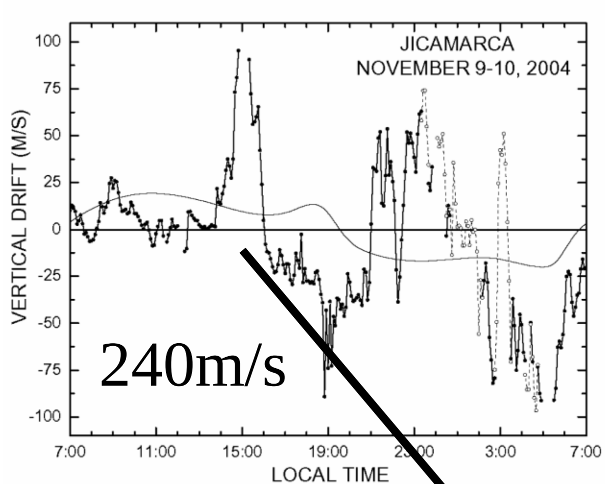


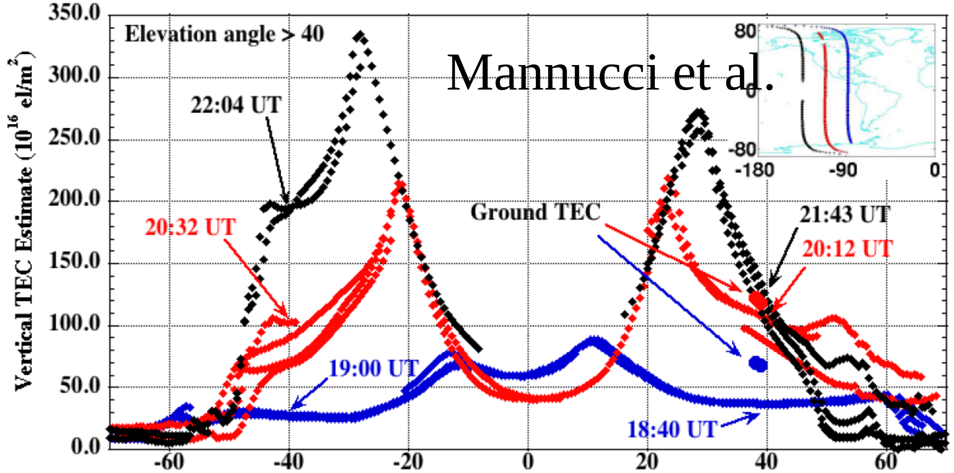


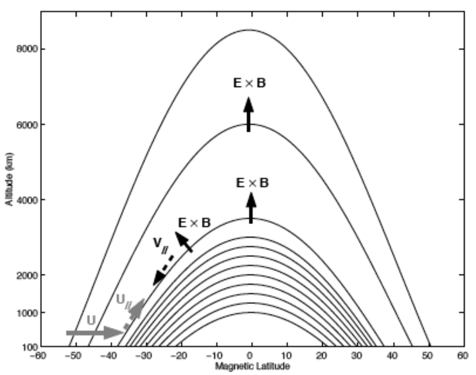
Courtesy Jerry Goldstein: IMAGE

Ionospheric response:

expect interaction between poleward movement and plasma increase in EIA due to penetration electric field and build-up of mid-lat plasma by the Heelis effect







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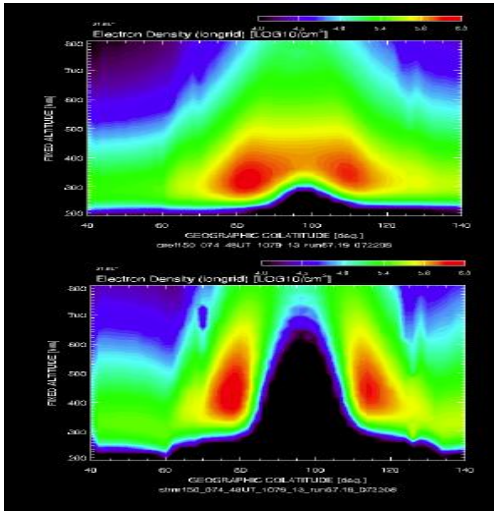
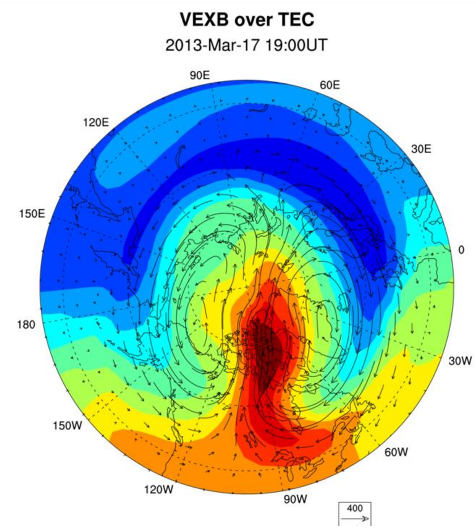
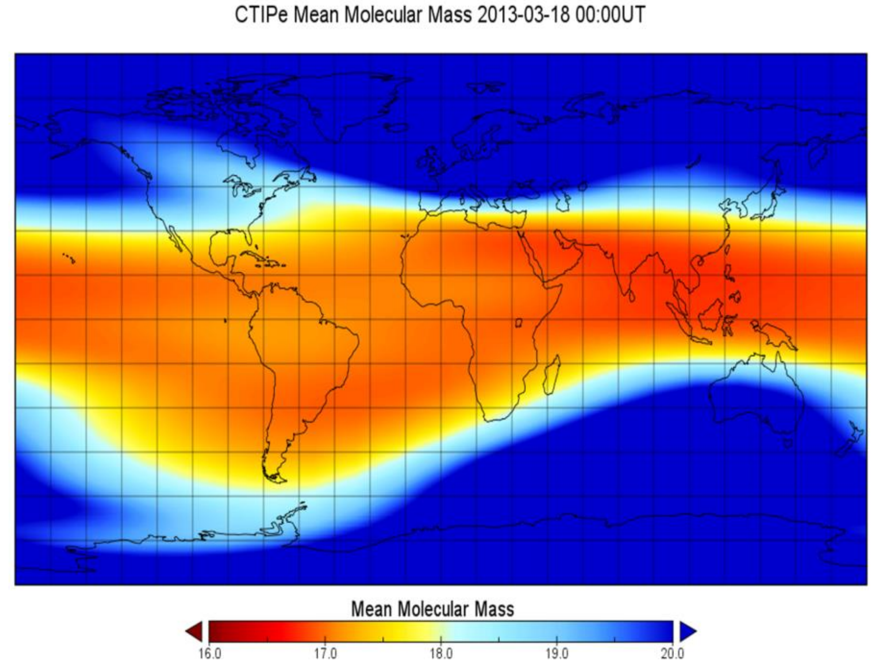


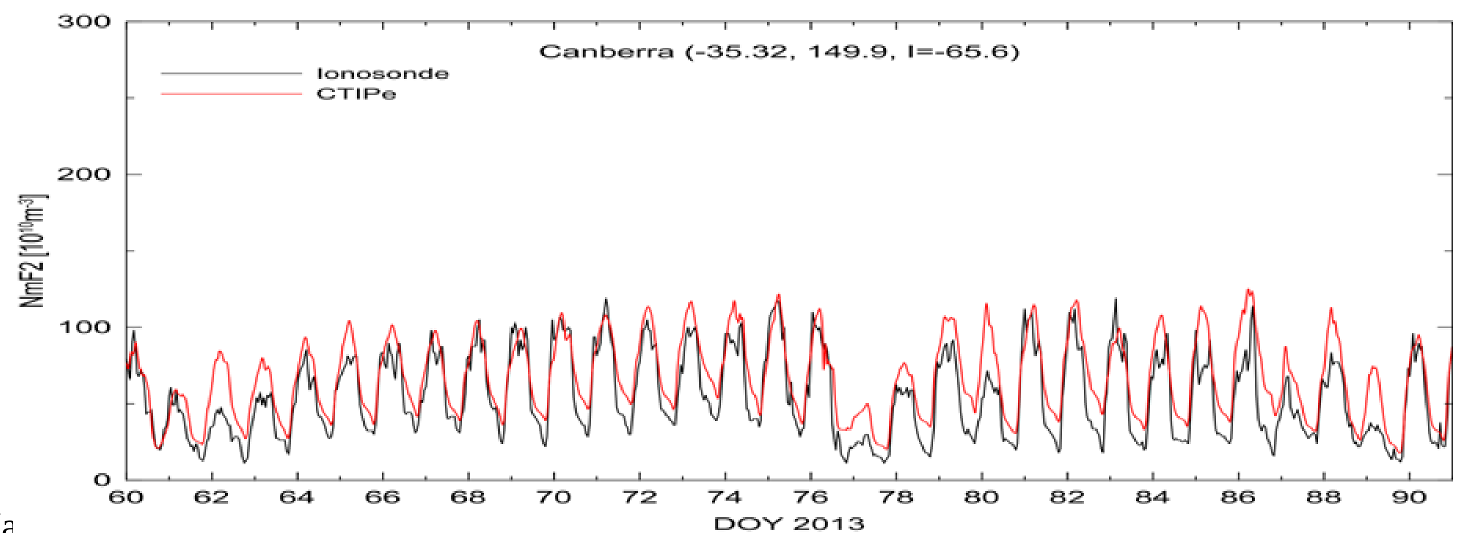


Nair estimated vertical plasma drift of 240 m/s

Ionospheric positive storm due to expanded convection, "Heelis mechanism" (Maruyama et al.)

Neutral composition change and the “negative phase”

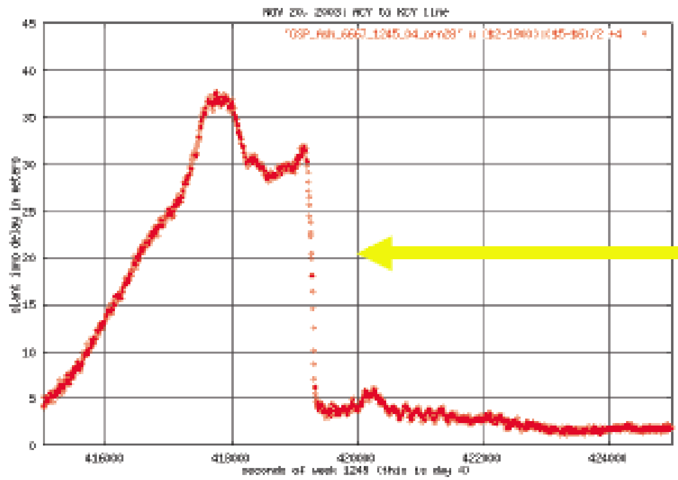




Conclusions

- Main sources of extreme space weather events are enhanced solar EUV and a Carrington-like CME driving an intense geomagnetic storm
- Heating from either expands the atmosphere, increasing satellite drag to higher altitudes ~1000 km, impacting collision avoidance in a region of a lot of 1 kg size tracked debris
- Ironically expanded atmosphere will help to clean out debris
- Ionospheric response more complicated – balance between plasmasphere erosion, mid-latitude positive phase, and poleward movement of equatorial ionization anomaly
- Unclear if neutral composition change and “negative phase” will be as effective

Storm Enhanced Density – Impact on Aviation

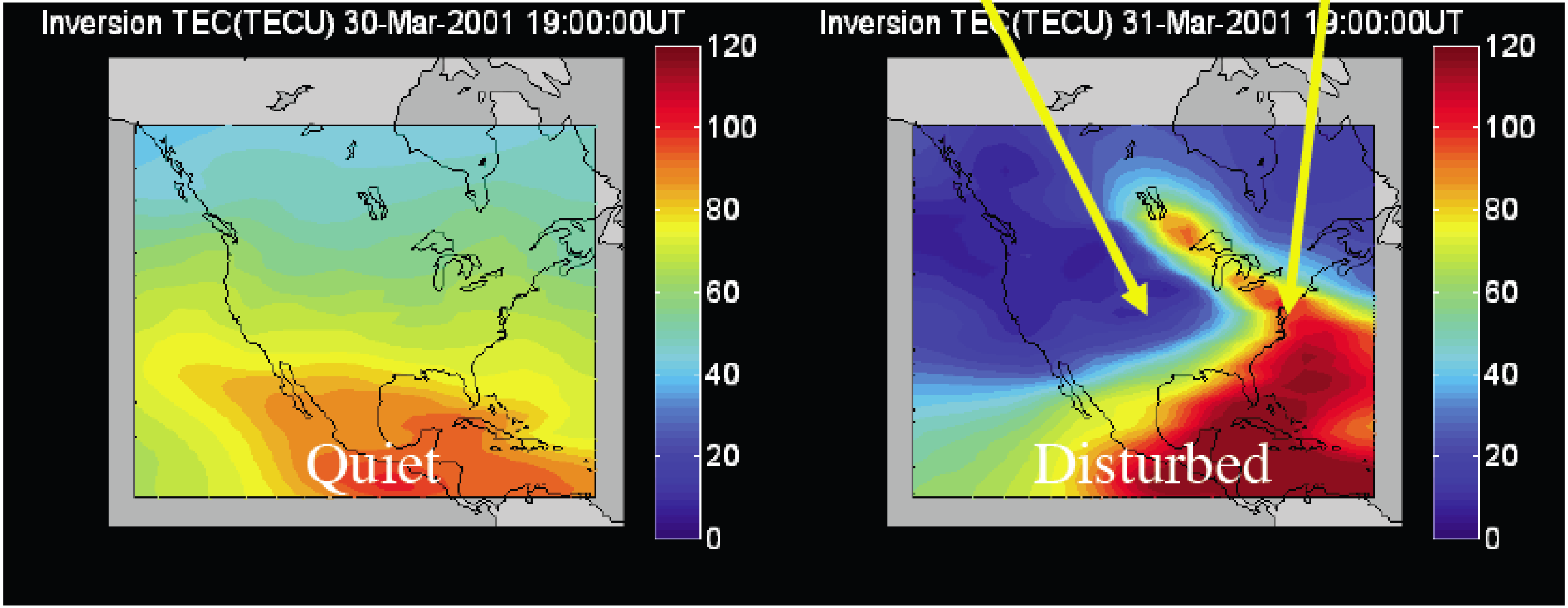


Stationary "walls" of TEC compromise integrity of aviation navigation

130 TEC units over 50 km
20 m of GPS delay;
walls move 100 to 500 m/s

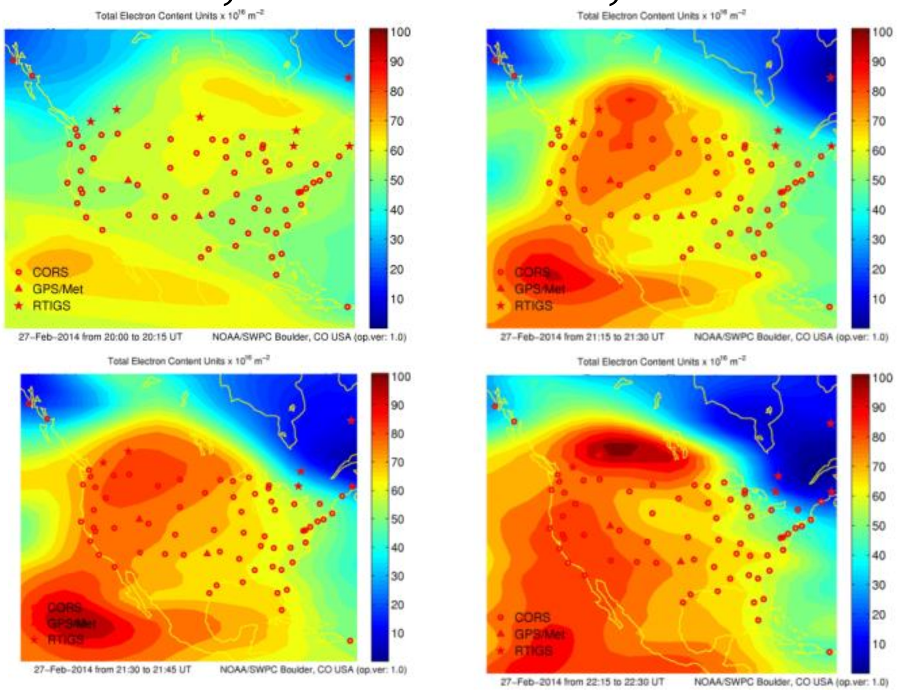
"negative phase"

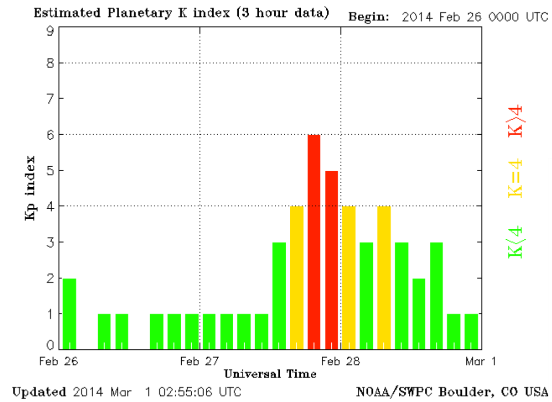
"positive phase" and tongue of ionization

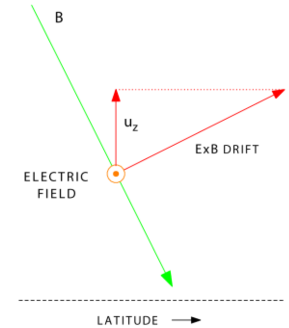


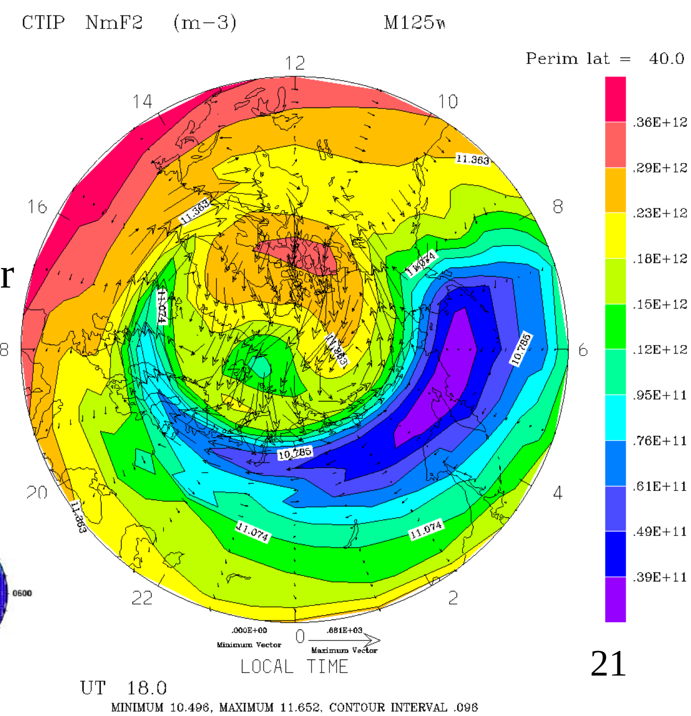
TEC response to expansion of magnetosphere convection

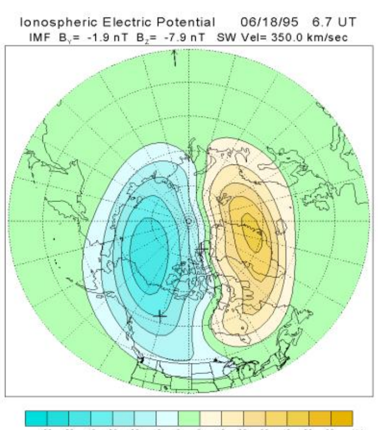
US-TEC, Feb 27th 2014, SWPC







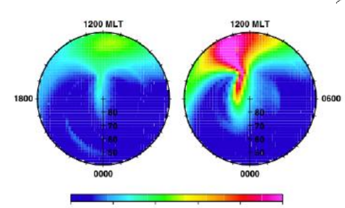




Weimer magnetospheric convection pattern as seen in the ionosphere

- Ionosphere TEC response time ~1 hr
- Response in particular longitude dependent on UT
- Forecast of solar wind/CME arrival time critical 2-3 hrs

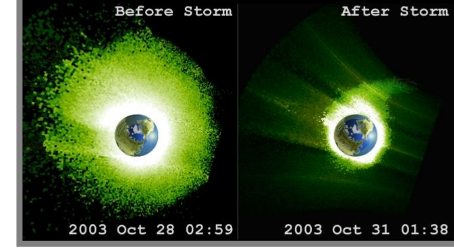
Heelis et al.

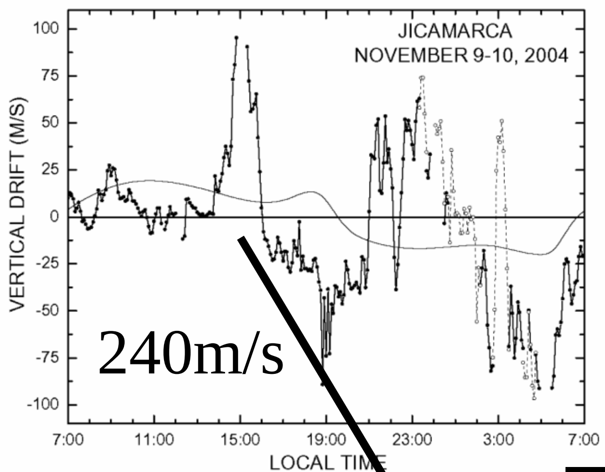


Conclusions (2)

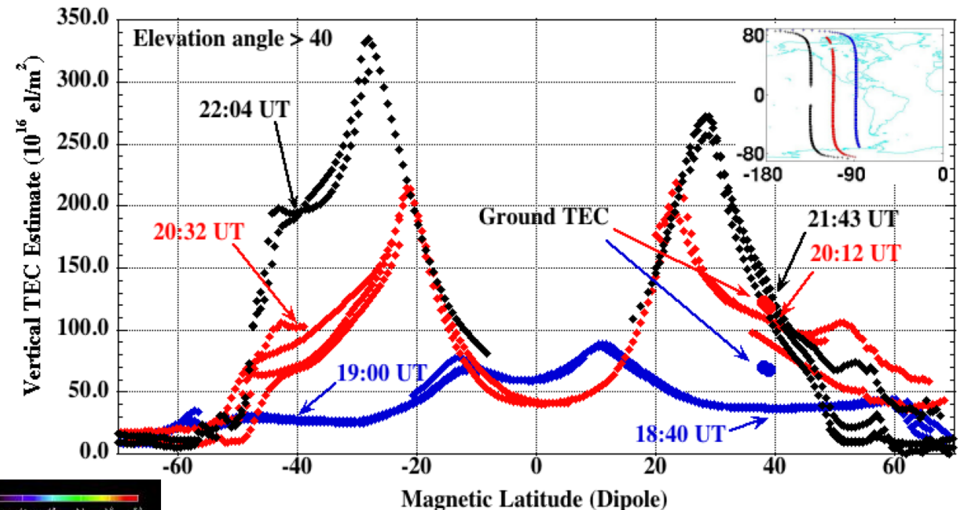
- NO production and infrared cooling limits atmosphere expansion and make the thermosphere colder in aftermath of storm
- Storm circulation no longer pole to equator. Energy input at mid-latitude, energy spreads (fills in) quickly by wind and wave transport globally
- Neutral composition change weaker as a result; clear negative ionospheric phase might not be so apparent, not clear if this is true for more realistic magnetospheric driver with more structure
- Expect interaction of poleward movement of EIA by penetration electric field (240 m/s vertical plasma drift from Nair model) and build up of plasma at mid latitude by “Heelis” effect
- Expanded polar cap and magnetospheric convection will erode plasma down to mid latitude (plasmasphere erosion)

Overlap between plasma increase due to penetration electric field and Heelis effect

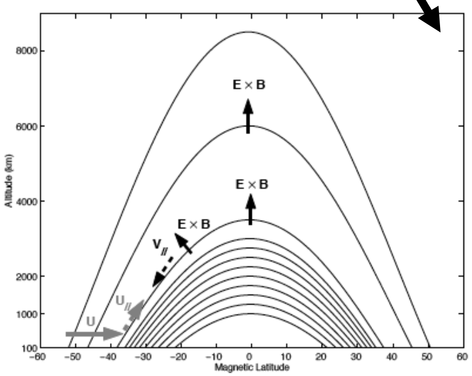




240m/s



Mannucci et al 2005



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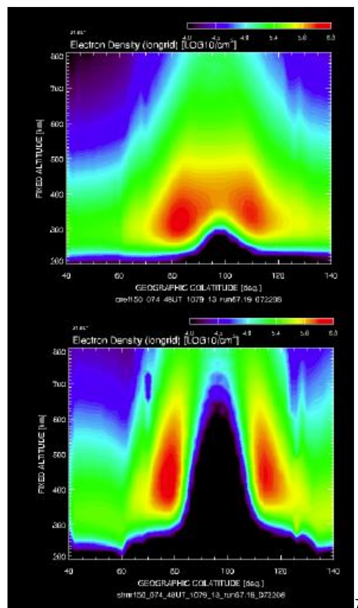

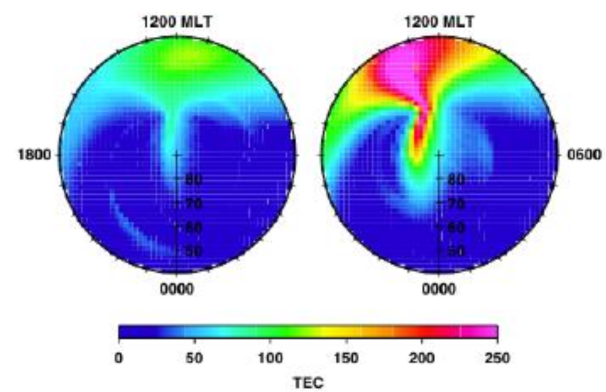

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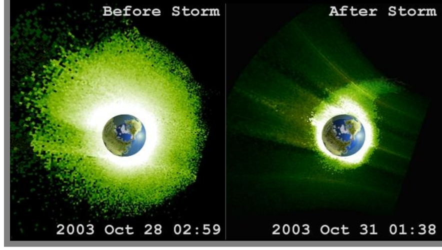
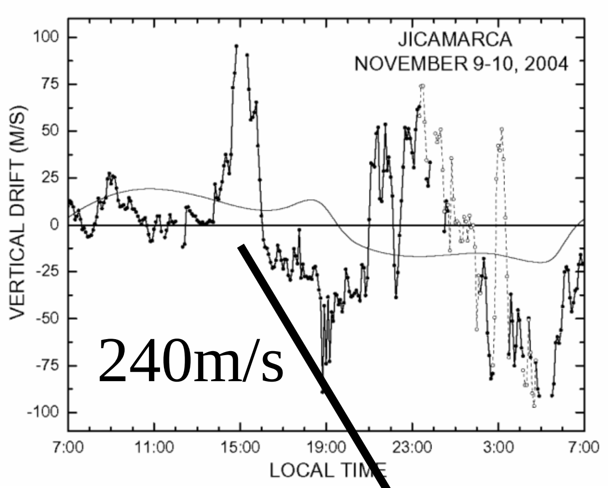
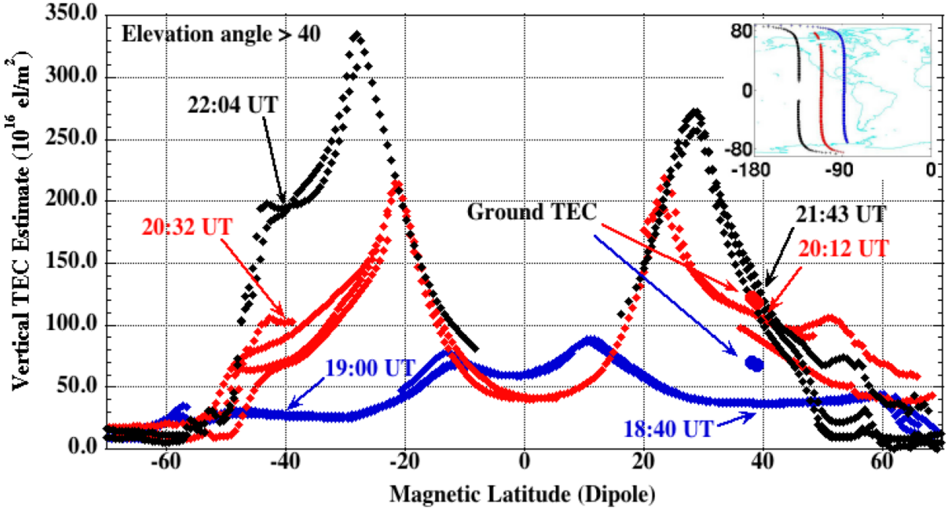
Ionospheric positive storm phases due to convection expansion (Heelis et al.)

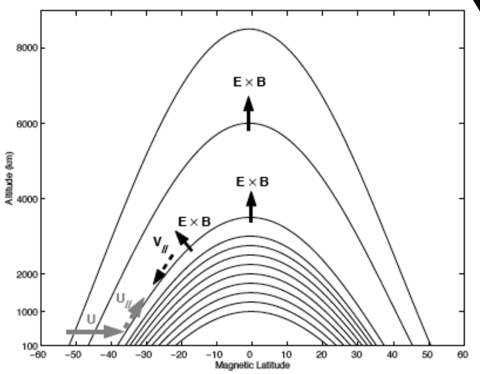
Ionospheric response: expect interaction between poleward movement and plasma increase in EIA due to penetration electric field and build-up of mid-lat plasma by the Heelis effect







Mannucci et al 2005



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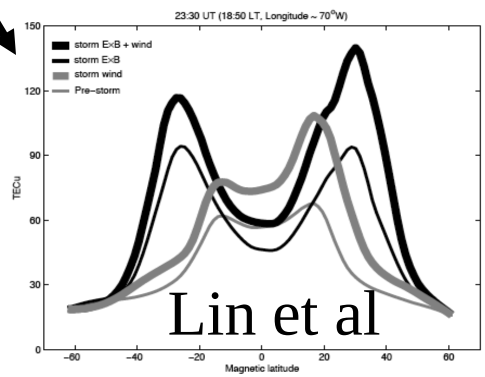
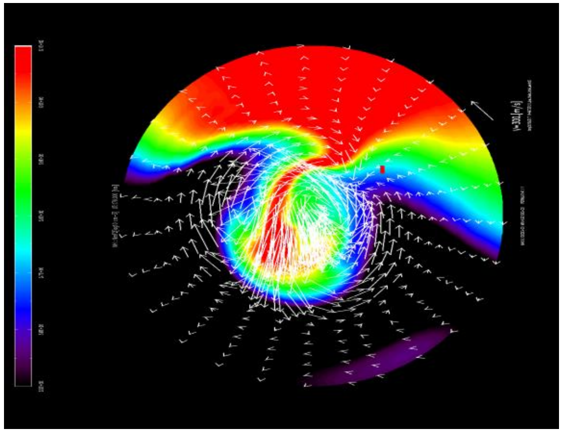


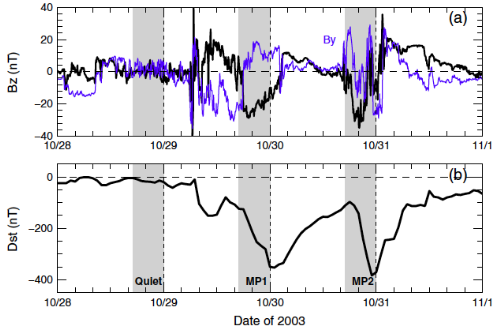
Figure 10. The total electron content (TEC) between altitudes 100 and 2000 km from the SUPIM results at 23:30 UT (18:50 LT) at -70° geographic longitude on the pre-storm day (thin gray line), case 1 (bold gray line), case 2 (thin black line), and the case 3 (bold black line).

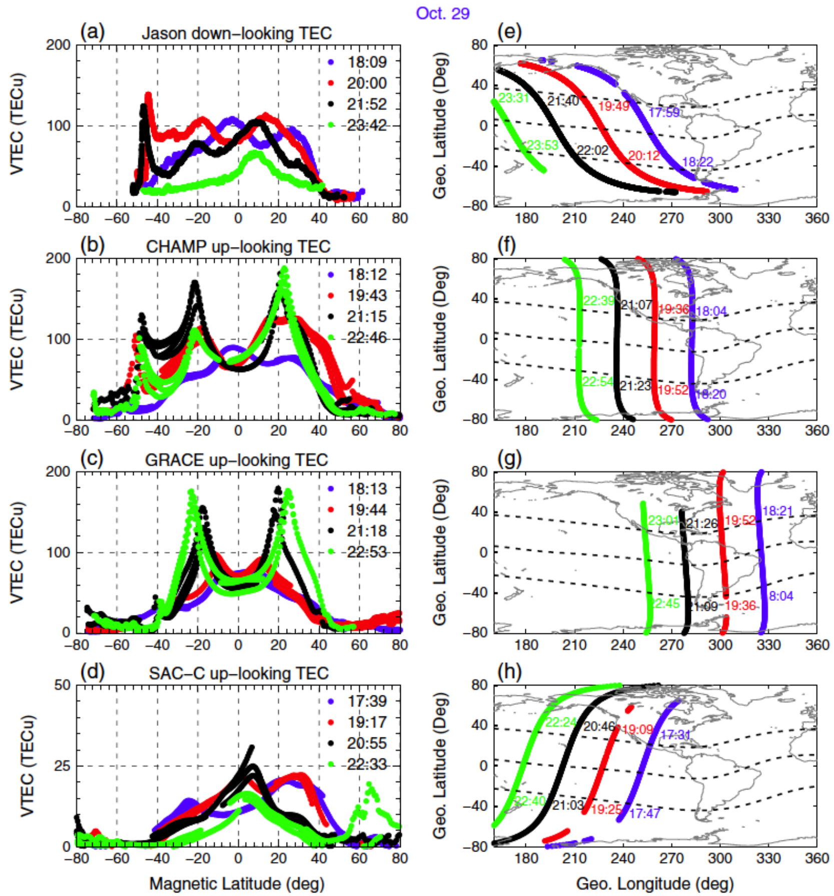


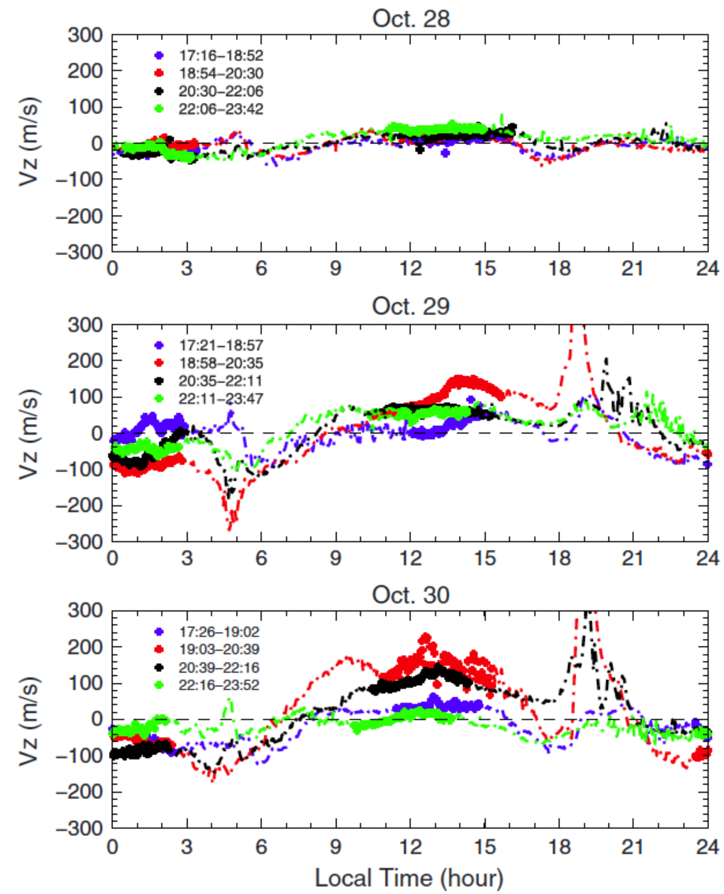
Nair estimated vertical plasma drift of 240 m/s

Ionospheric positive storm due to expanded convection, Heelis mechanism (Maruyama et al.)

Halloween Storm Lei et al. 2012
Clear distinction between equatorial ionization anomaly peaks and “SED”

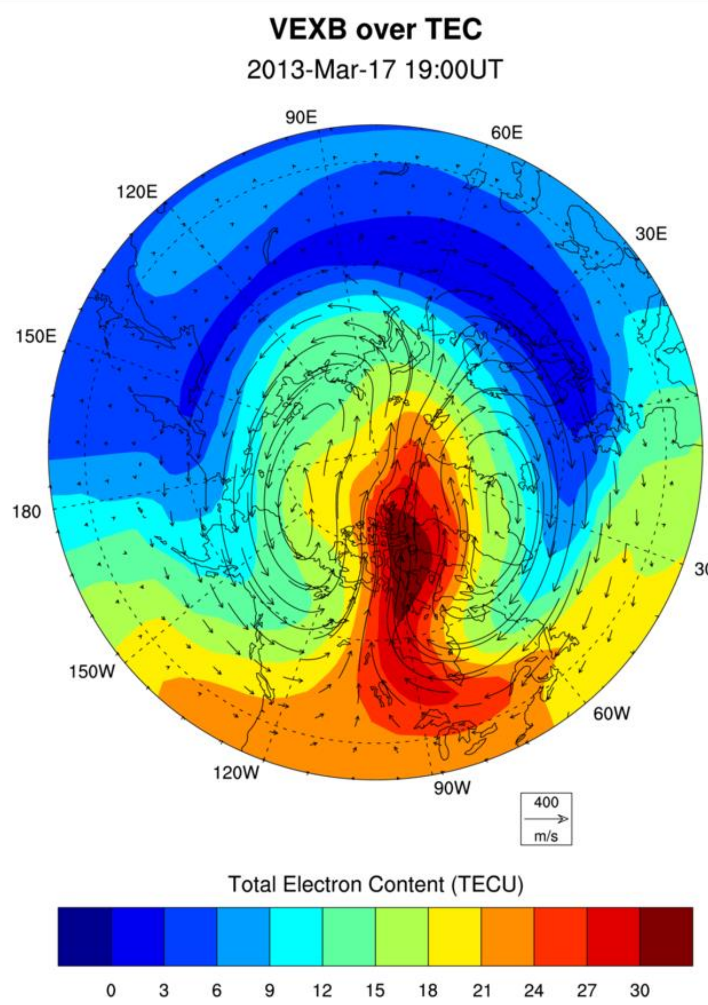


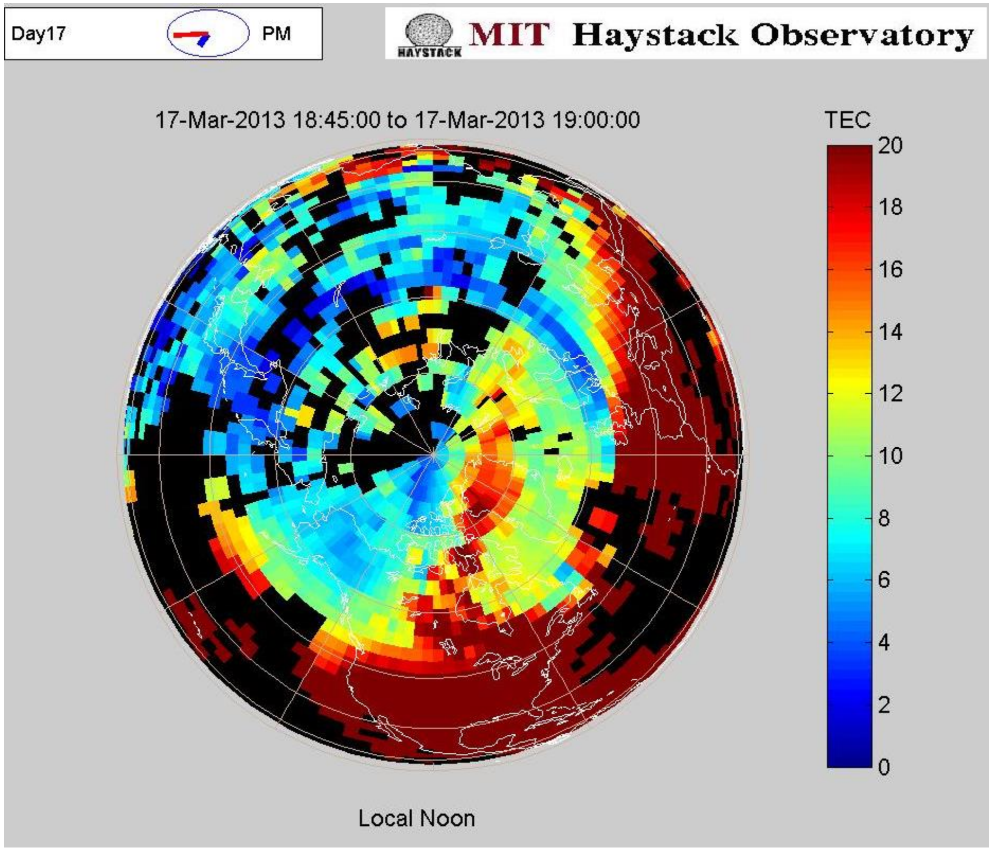




Vertical TEC above satellite altitude illustrates vertical distribution of plasma and storage of plasma in topside

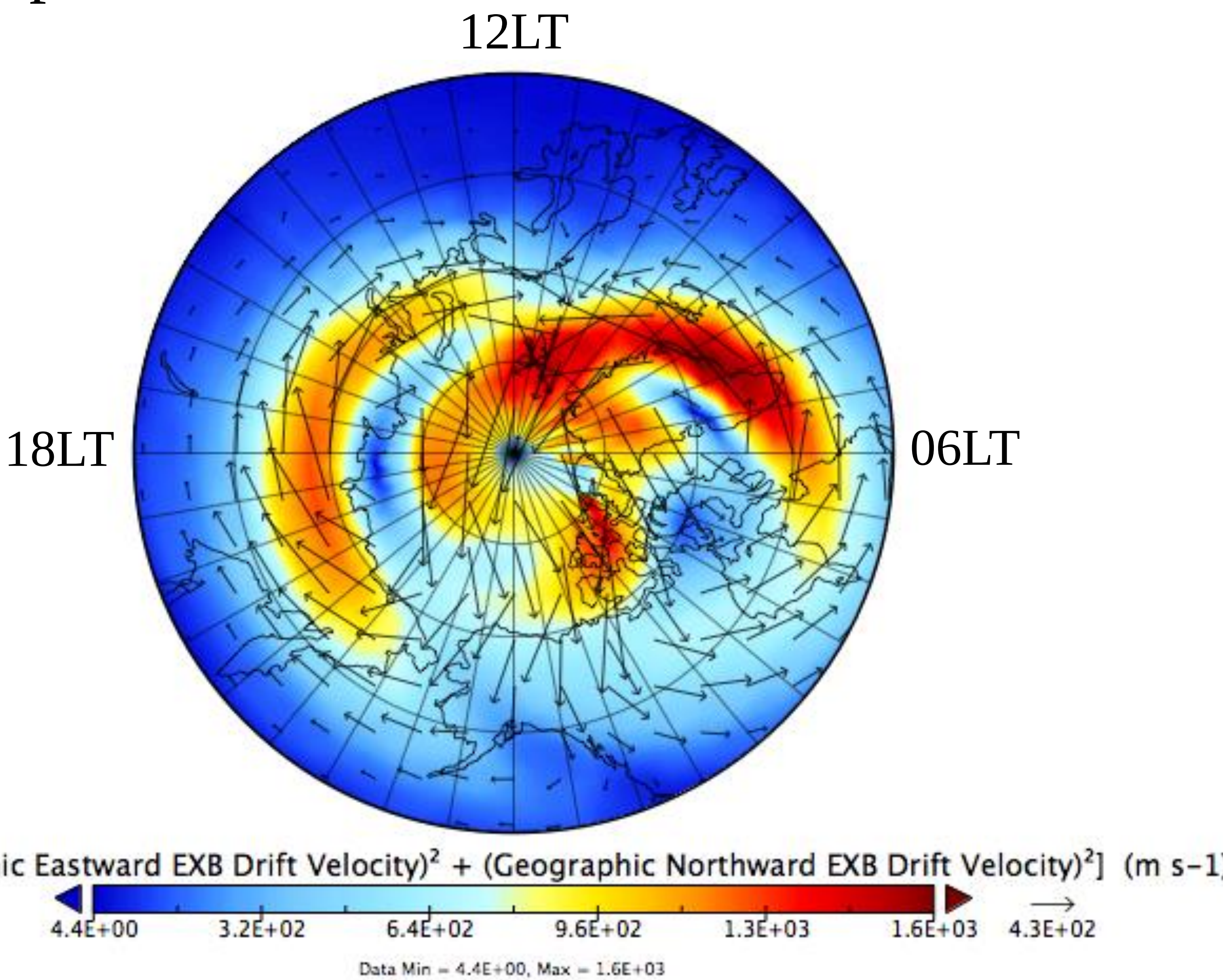
19UT March 17, 2013
Northern Hemisphere



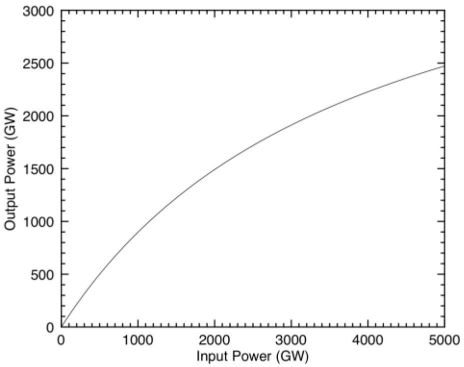


Anthea Coster TEC maps MIT

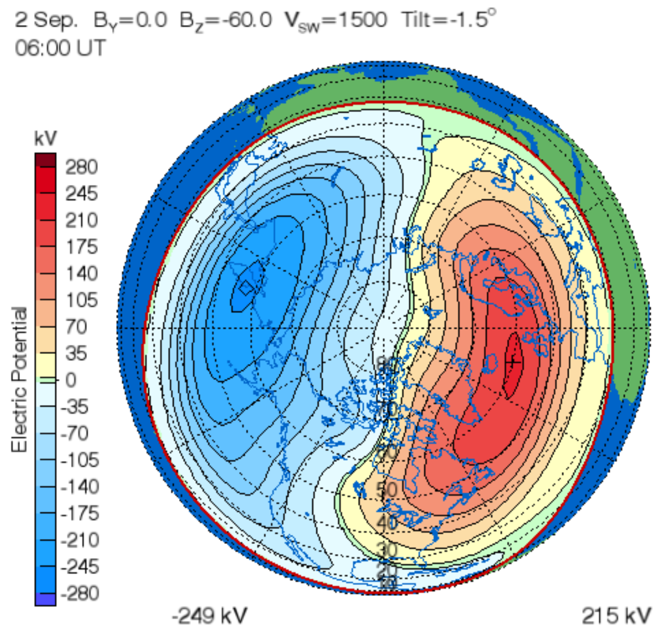
Weimer 2005 convection pattern plasma drift 10UT March 17, 2013

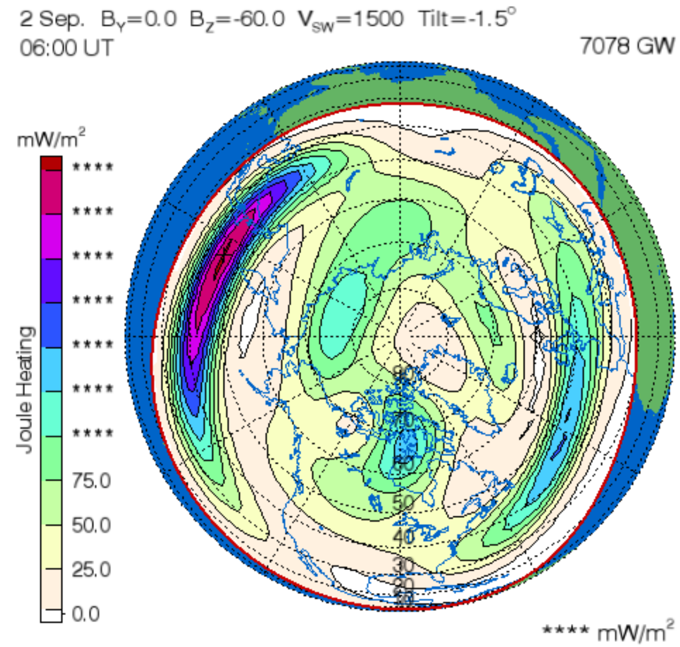


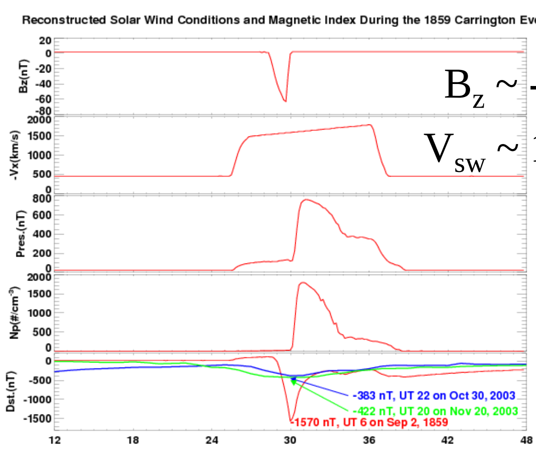
Weimer empirical magnetospheric convection predictions for Carrington event



Power reduced by saturation to 3000 GW





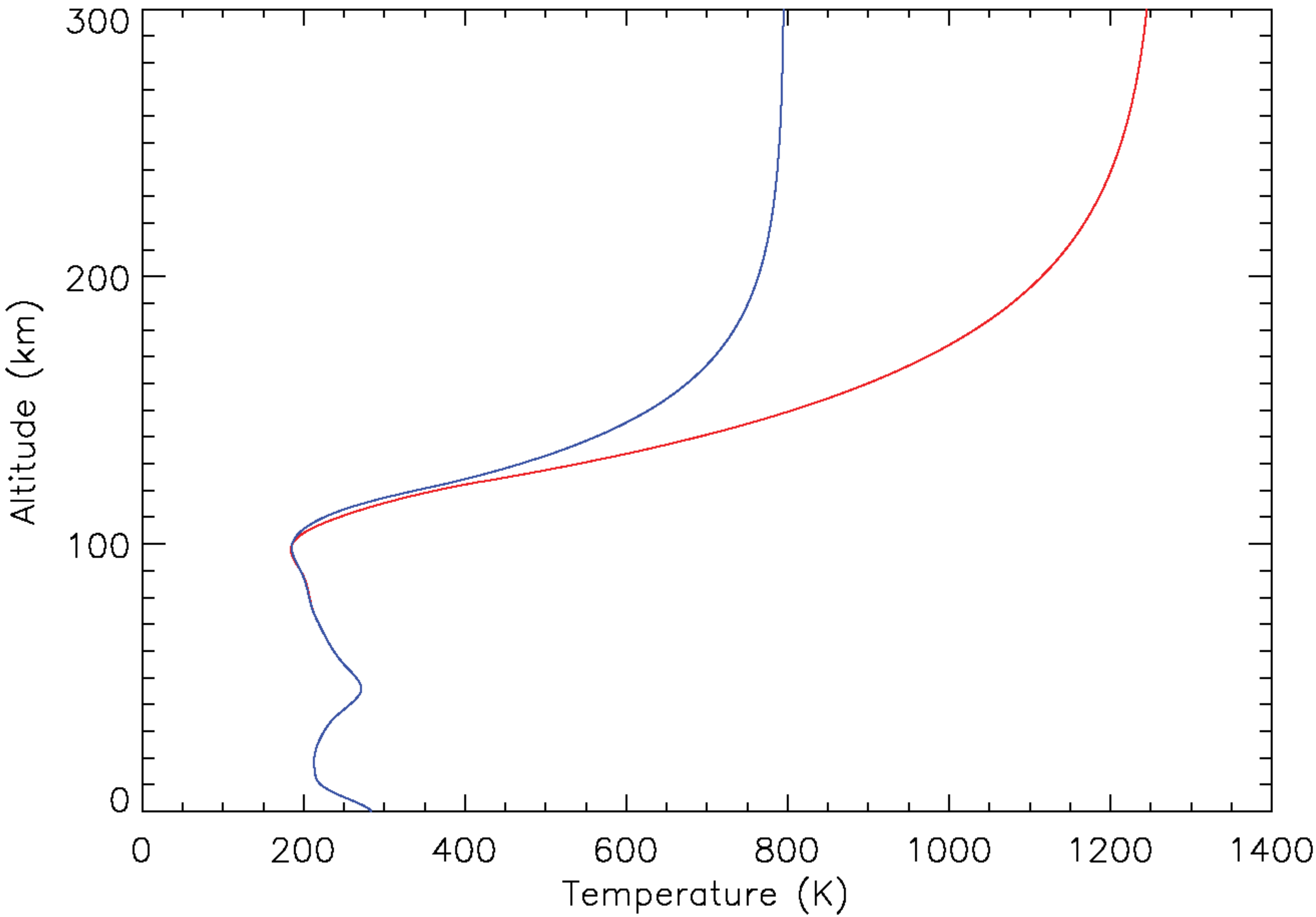


B_z ~ -60 nT

V_{sw} ~ 1800 km/s

Predicts the aurora over Cuba CPCP ~450kV, Joule heating/Poynting flux estimated to be 7000 GW in each hemisphere, reduced to 3000 GW by magnetospheric saturation

Temerin and Li [2002] & Li et al.[2006]



300
200
100
0
Altitude (km)
0
200
400
600
800
1000
1200
1400
Temperature (K)

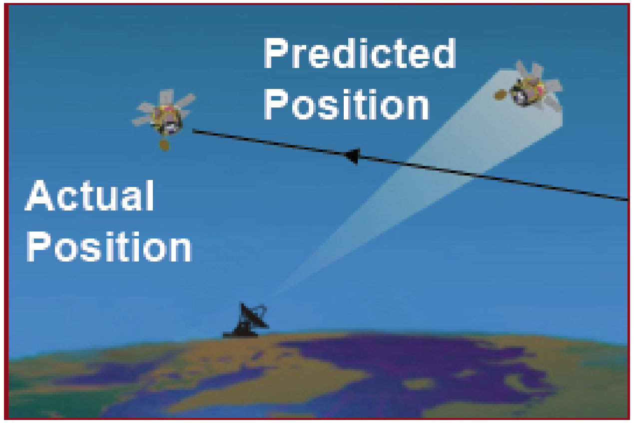
Preliminary estimates of benchmark for 100-year and theoretical maximum for a Coronal Mass Ejection

- Estimate of the response to a 100-year event are based on predictions of the solar wind drivers: interplanetary magnetic field (e,g., southward B_z), and solar wind velocity and density.

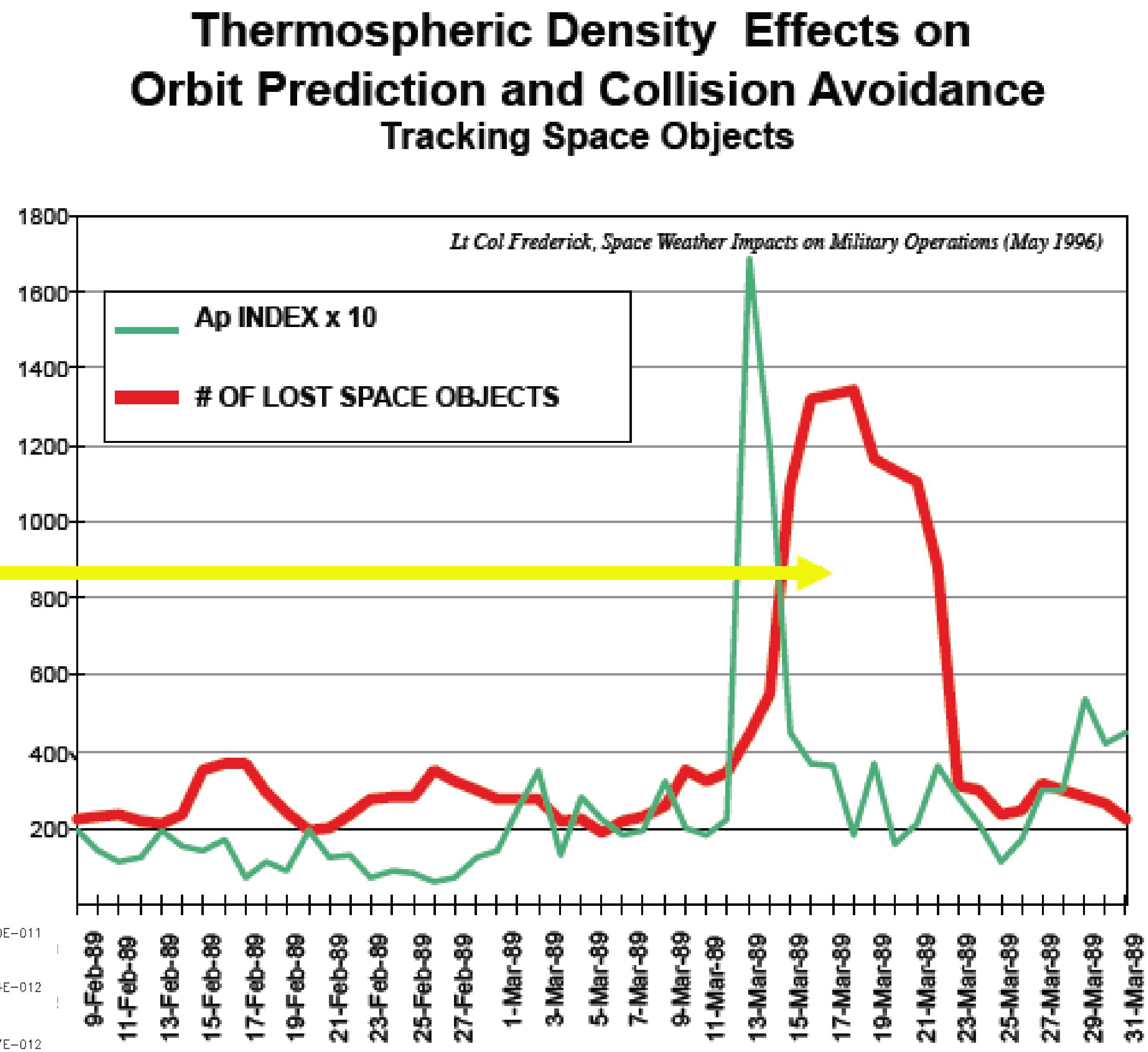
- Two events are often cited characterizing an extreme event: Carrington storm of 1859 and an event observed by STEREO A spacecraft in July 2012.

- Estimate of southward B_z are 60 to 70 nT, together with solar wind speed exceeding 2000 km/s, and solar wind density of ~60 cm^{-3}

- Relative response to storm depends on solar activity, larger density response at low solar activity (potentially important for tracking debris)

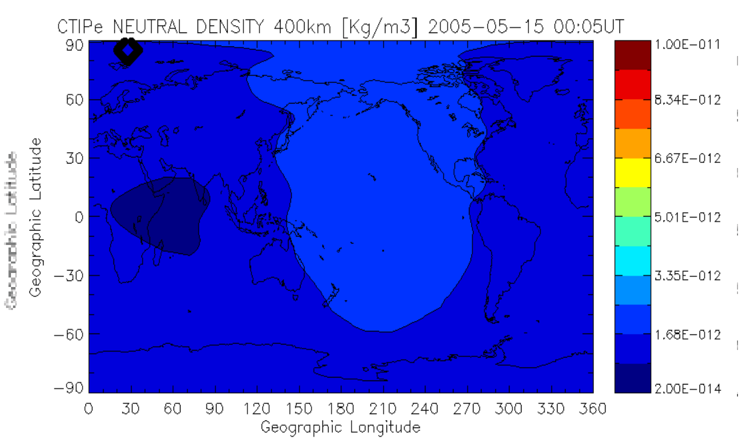


Tracking of Space Objects



During the geomagnetic storm of March 1989, more than 1000 objects were temporarily lost for a period of several days.

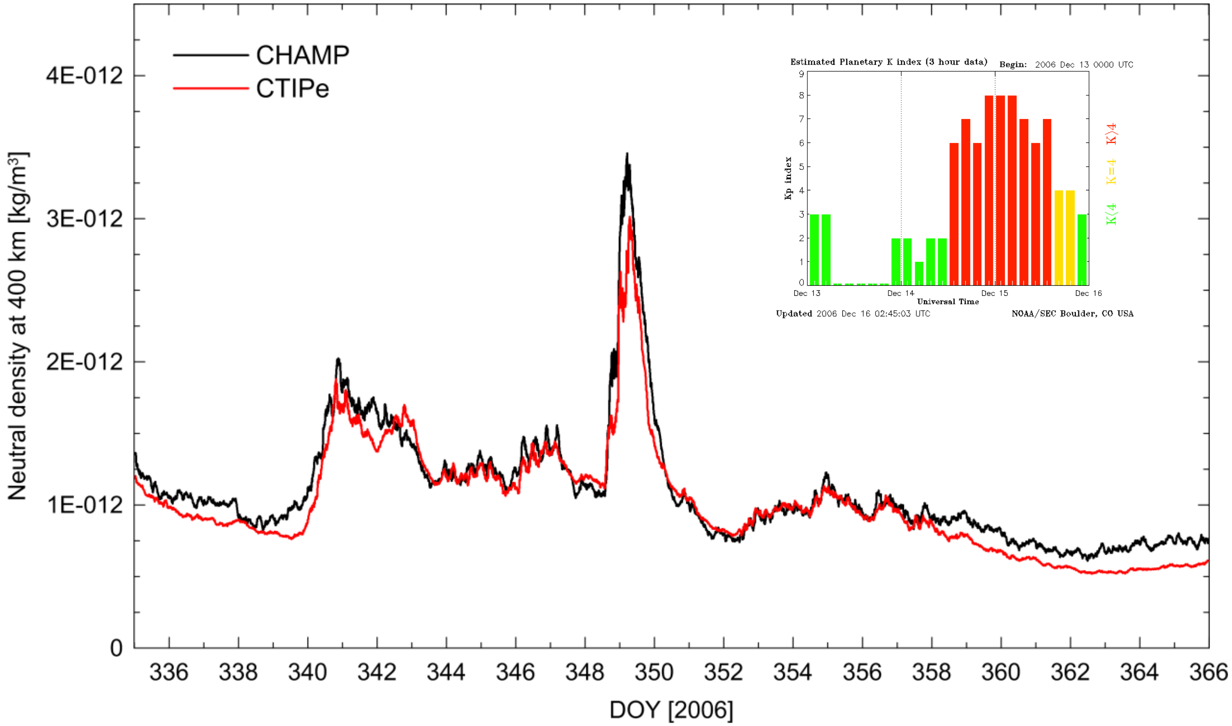
This was a direct effect of increased atmospheric drag on the orbiting objects caused by a severe geomagnetic storm.

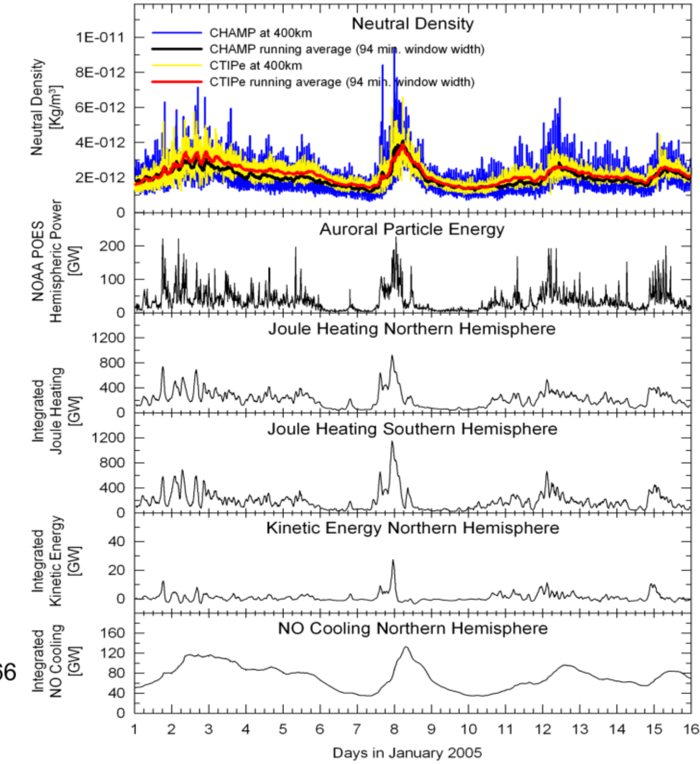


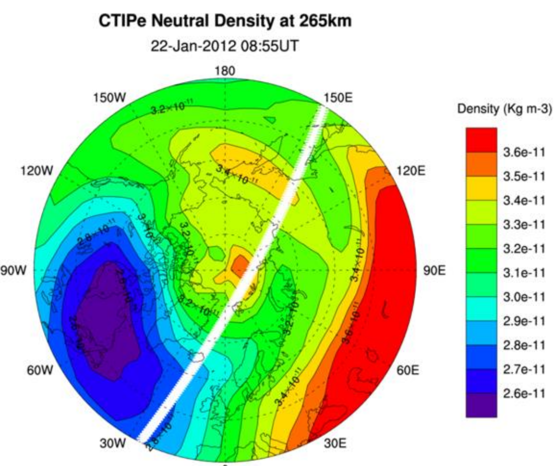
~20,000 pieces of debris > 5 cm are tracked

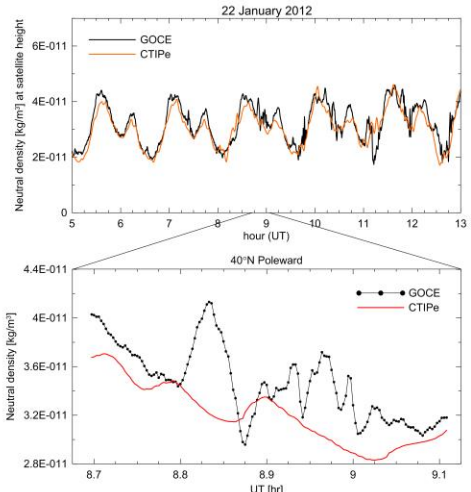
Collision between spent Russian satellite and Iridium and

CTIPe vs CHAMP or GOCE

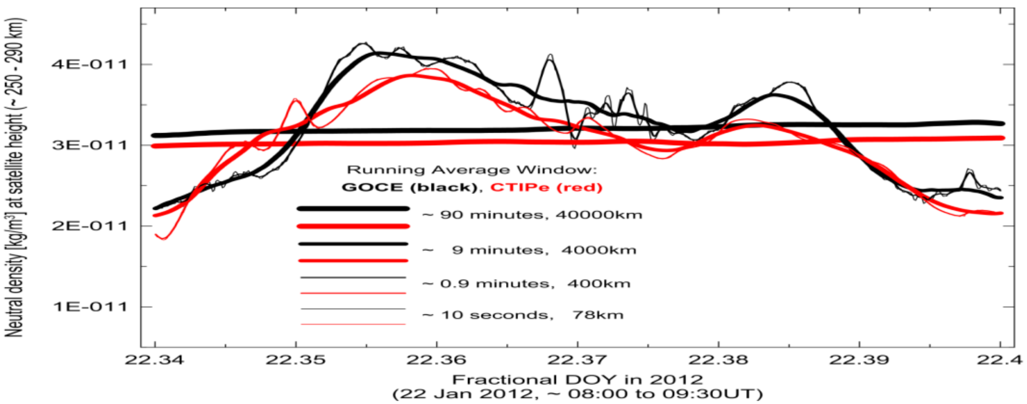


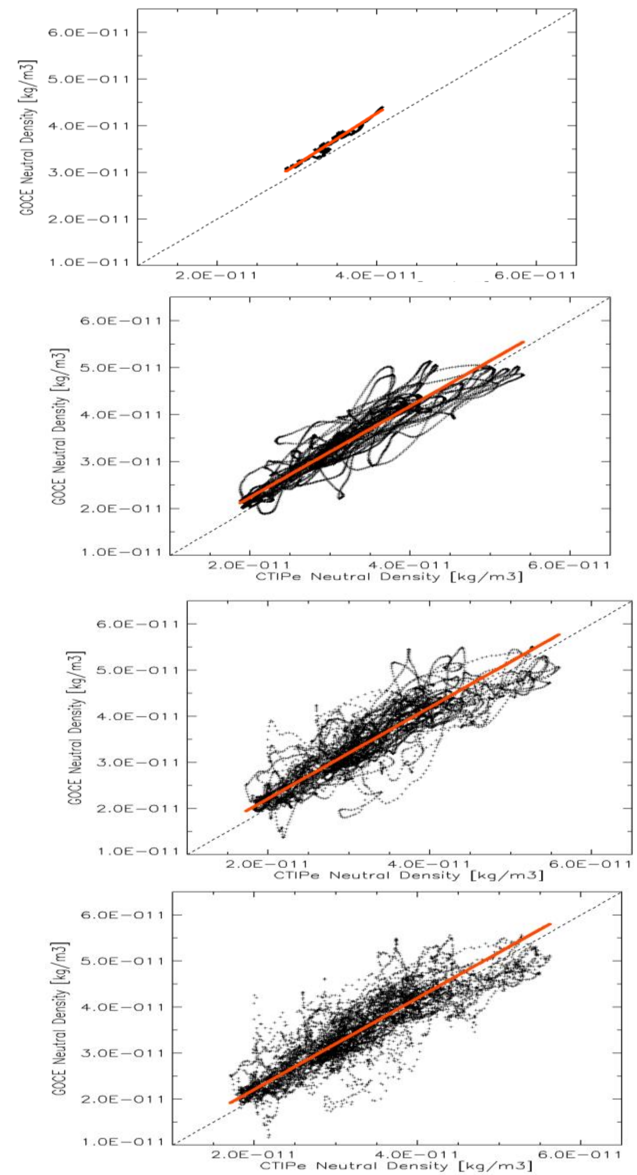






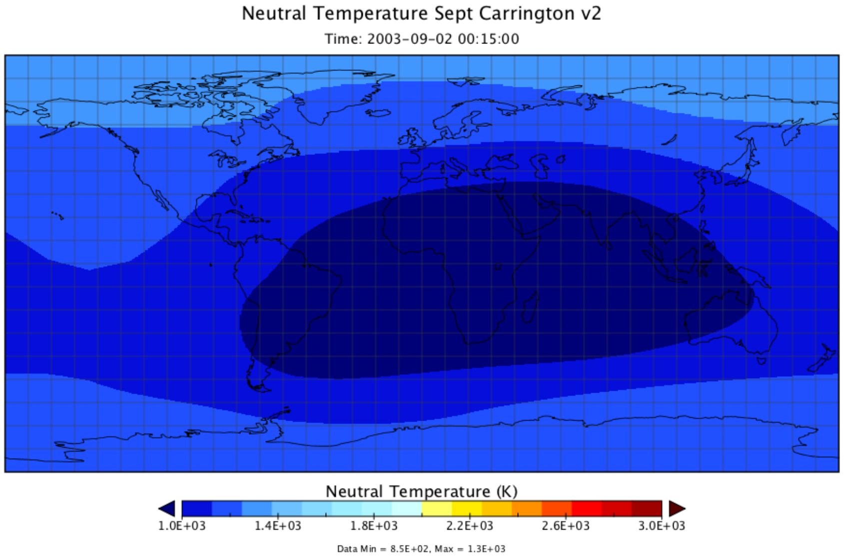
What would this density response look like during a Carrington event?





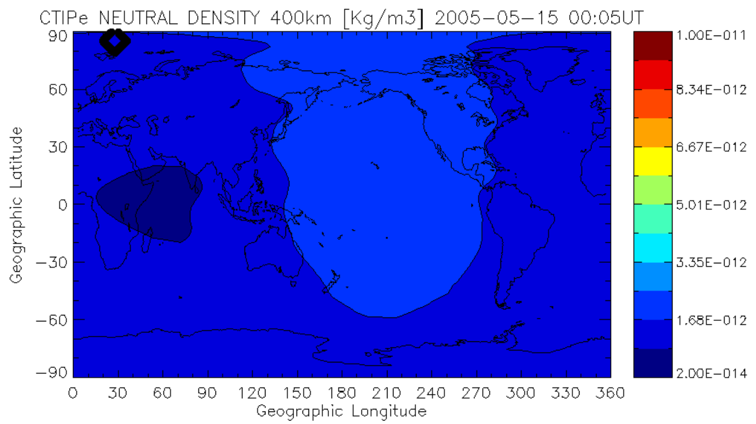
WINDOW (km)	R	RMSE	BIAS	SD
40000	0.986	0.060	0.059	0.015
4000	0.915	0.105	0.057	0.089
400	0.880	0.128	0.057	0.116
78	0.875	0.131	0.057	0.120

Peak temperature > 3000 K



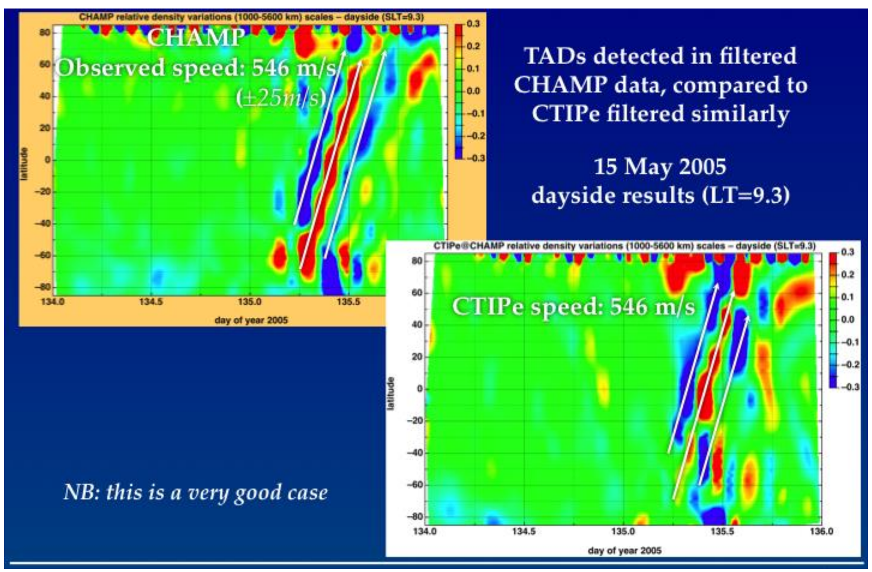
Gravity wave propagation from high to low latitude

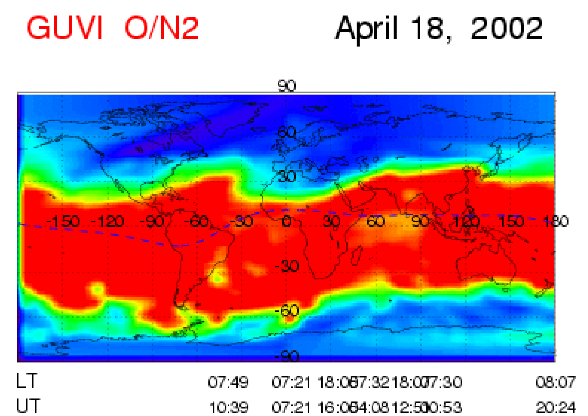
What speed and wave amplitudes of waves can we expect?



e.g., CHAMP density waves.

Can be a complicated superposition.





Bruinsma, Fedrizzi, et al.

How will the global circulation evolve, neutral composition change, and the ionospheric “negative phase”

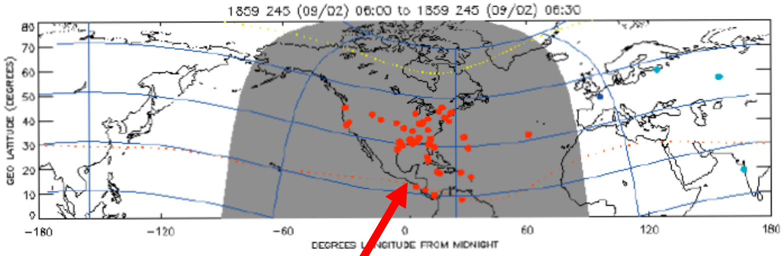
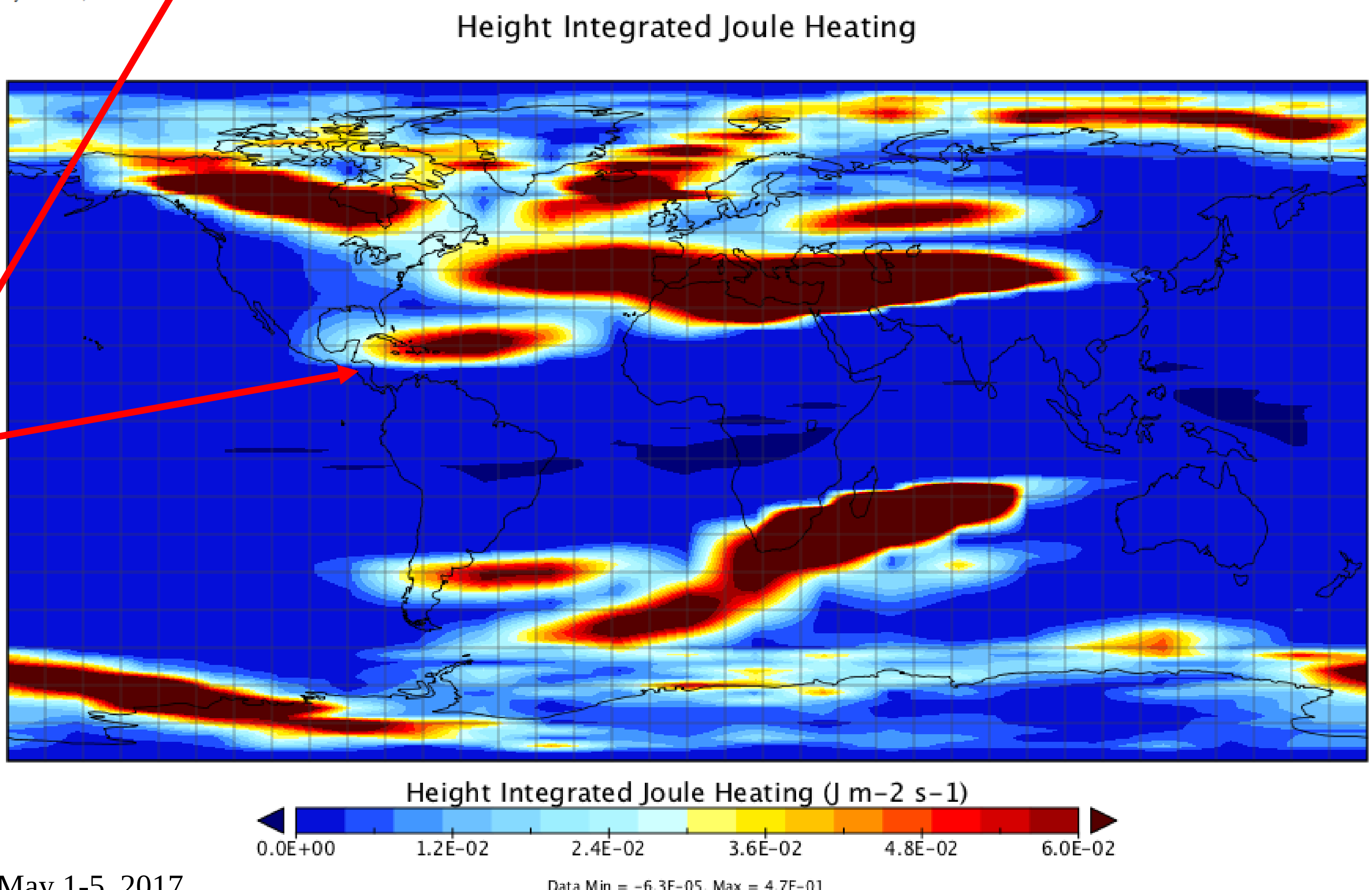


FIGURE 1.2 Locations of reported auroral observations during the first ~1.5 hours of the September 2, 1859, magnetic storm (orange dots). Courtesy J.L. Green, NASA

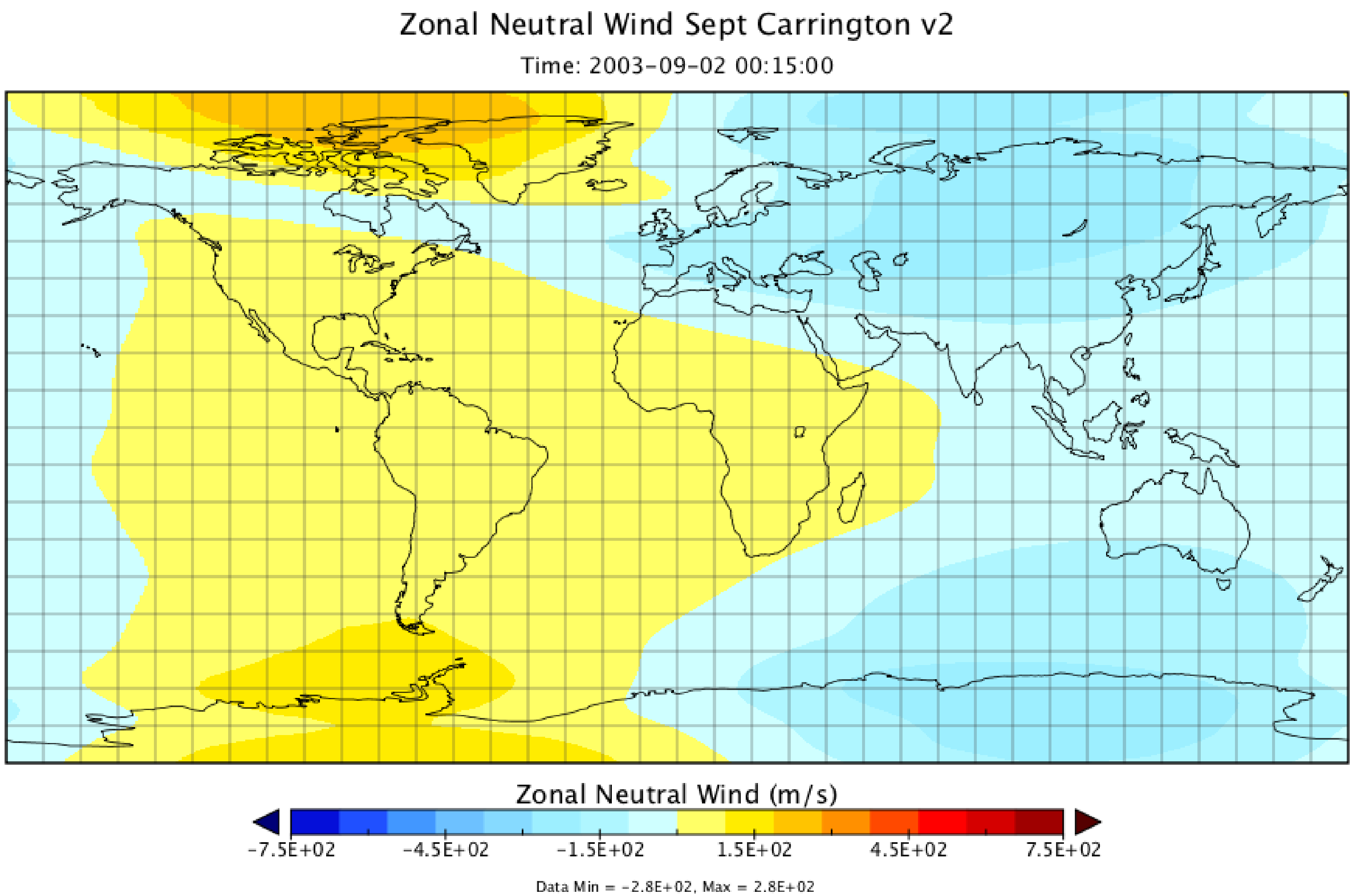
CTIPe Joule Heating:

location of energy injection is consistent with auroral observations

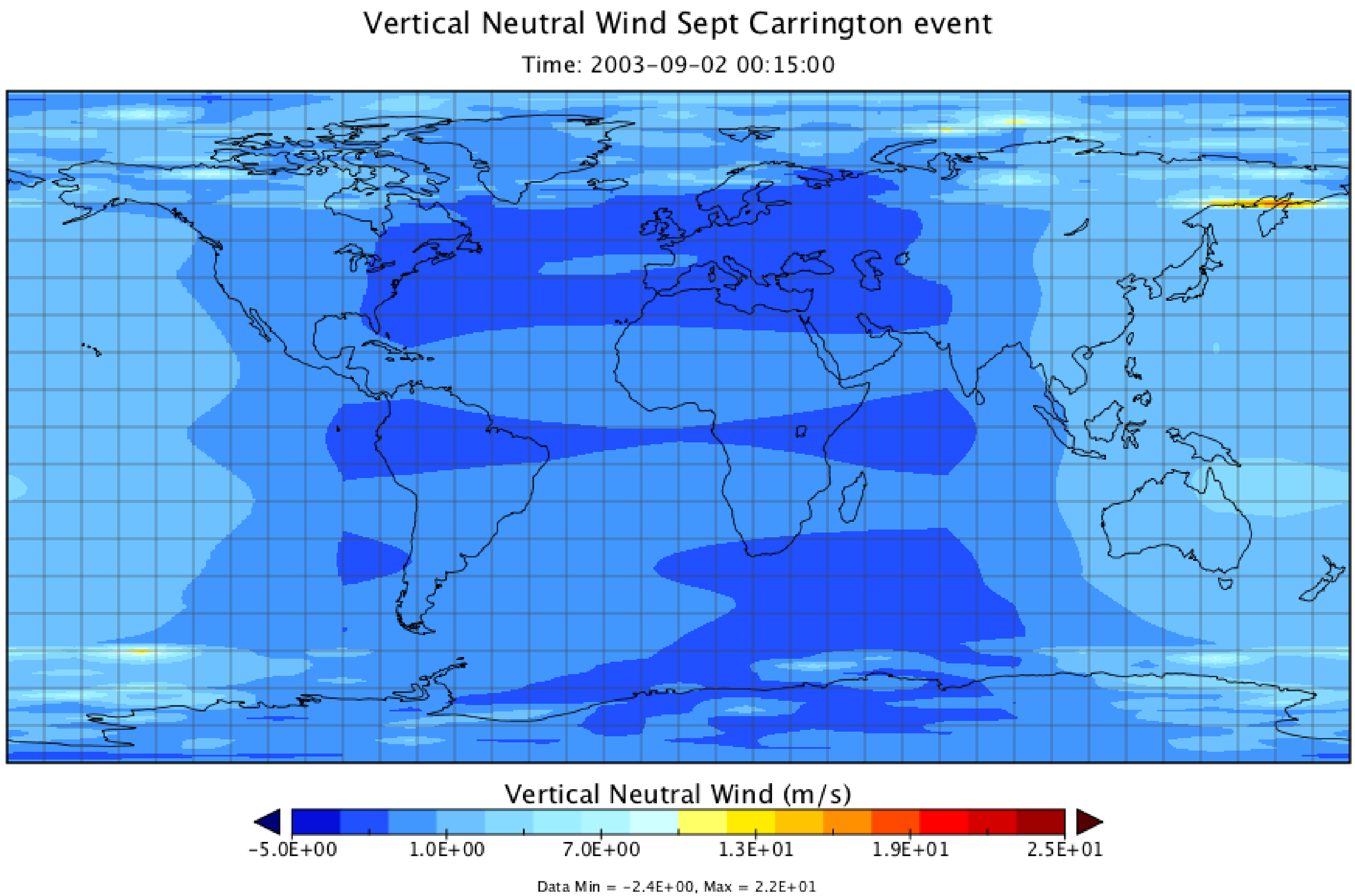


May 1-5, 2017

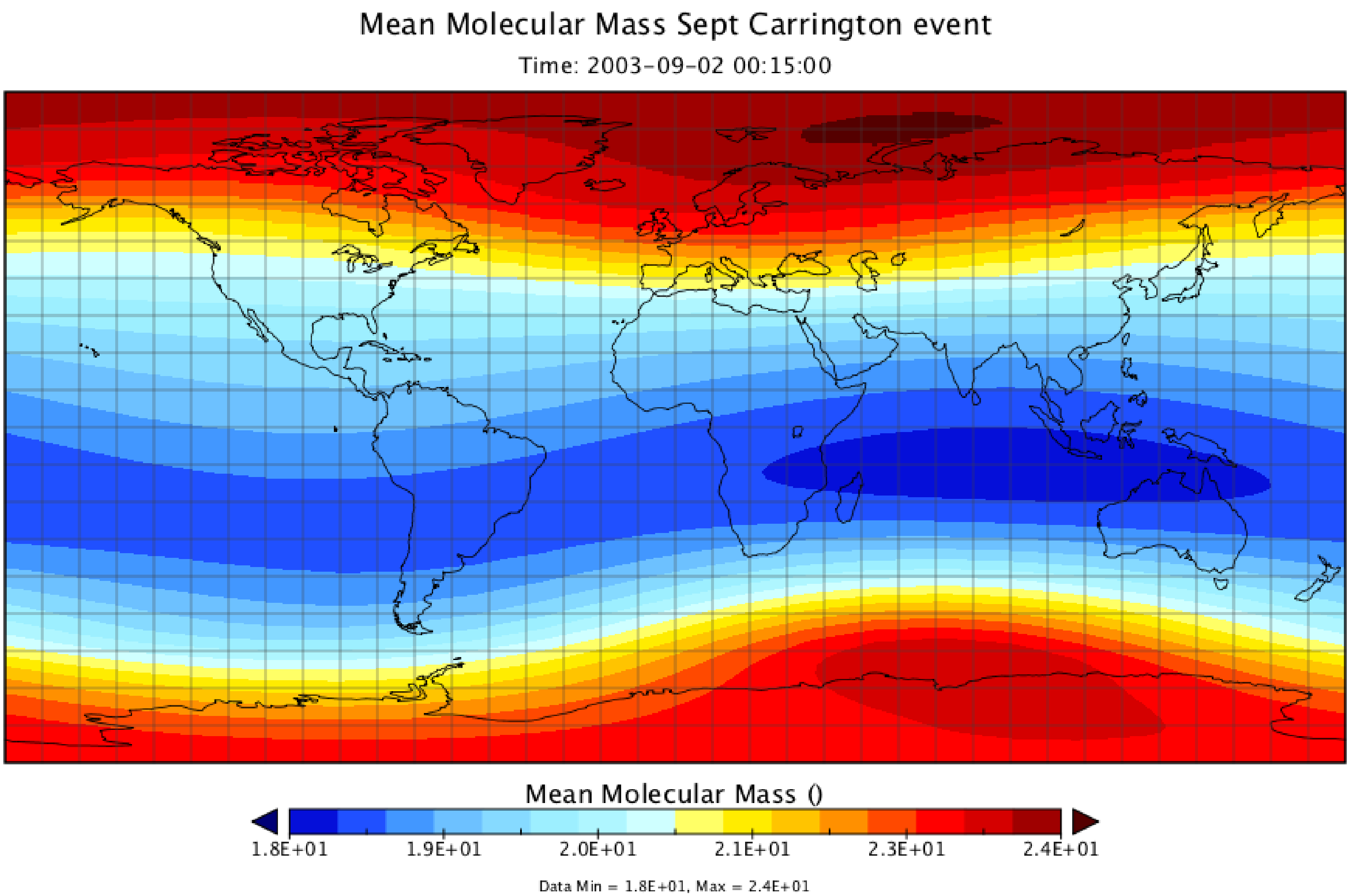
Horizontal winds > 1500 m/s



Vertical wind > 150 m/s

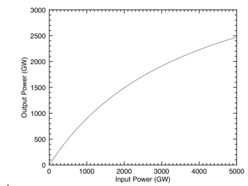


Mean molecular mass



Validation challenges

- Make sure at least we can model the biggest events: e.g., Halloween, Bastille, “Parents Day”, March ’89….
- Run MHD codes to check magnetospheric drivers of the system, expansion of convection equatorward, polar cap boundary, penetration electric field, inner magnetosphere shielding, degree of structure, etc.
- Compare OpenGGCM, SWMF, LFM for consistency
- Will the magnetospheric CPCP completely saturate?



- Need a time dependent and more expanded polar cap boundary for the ionosphere – for escape of plasma, plasmasphere erosion, location of the plasmapause – will we lose most of the ionosphere for a few days?
- Ionospheric response will depend heavily on the magnetospheric drivers
- Thermosphere-ionosphere response will have to rely on understanding the physical processes – does it make sense? (interaction of EIA and SED, penetration electric field and neutral wind dynamo)

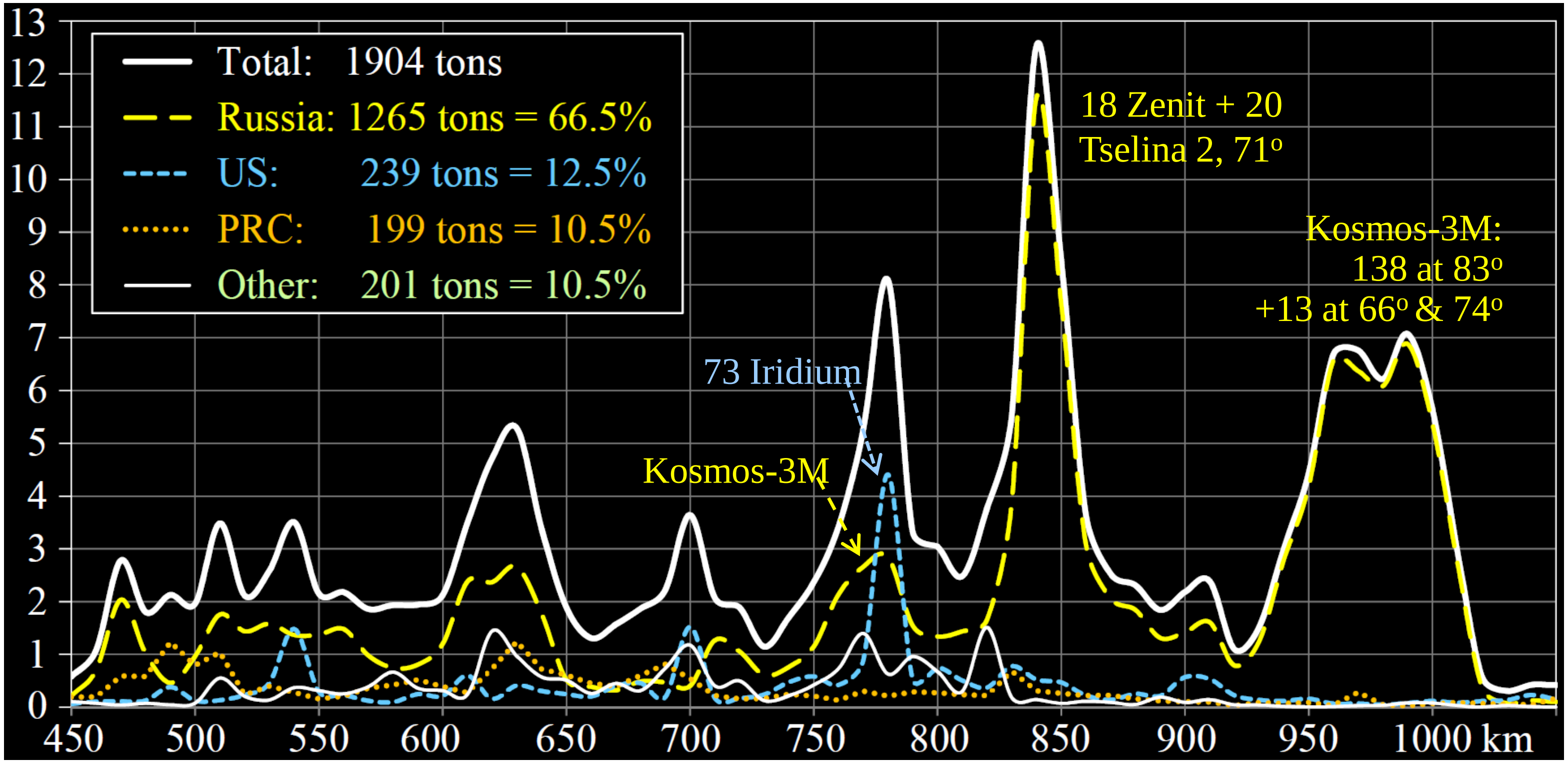
Preliminary benchmark for response to 100-year geomagnetic storm

Percent difference of global mean or orbit averaged neutral density response above empirical model values during Halloween or Bastille Day storms, at a median solar flux ($F_{10.7}$ 150) at 400 km altitude:

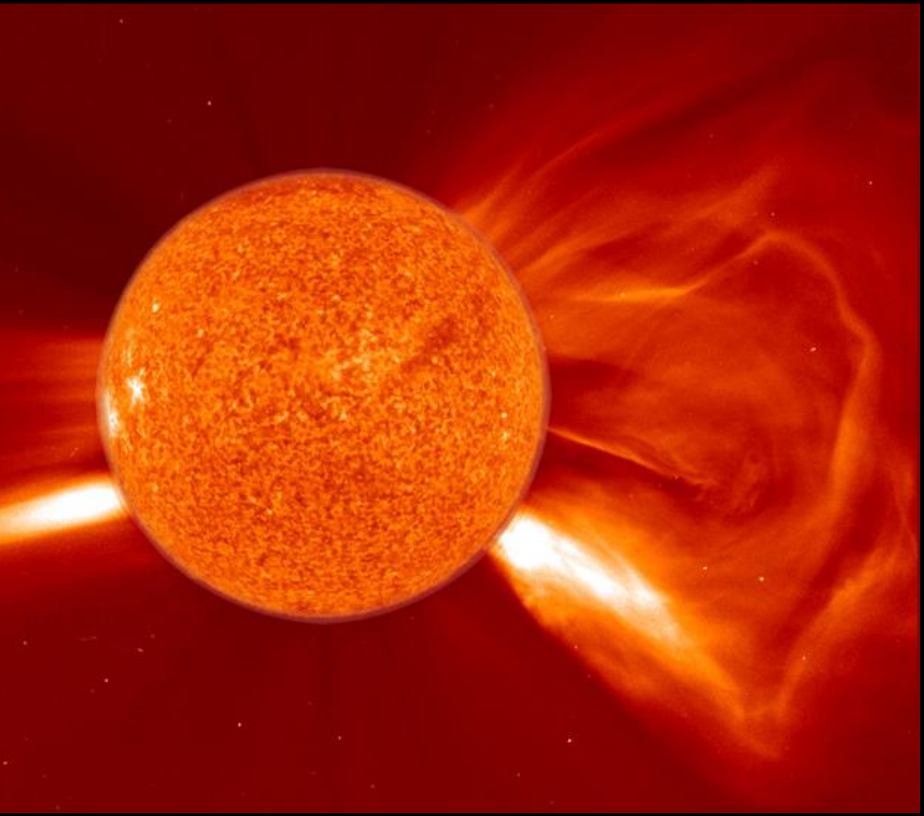
Altitude	100-Year Benchmark percent increase in response above values experienced during Halloween or Bastille Day storms	Theoretical Maximum percent increase in response above values experienced during Halloween or Bastille Day storms
400 km	400%	Phase 2

- Thermospheric temperature exceeds 4000 K, neutral winds ~2000 m/s
- Expect neutral composition changes modulate response by +/-50%, 500 km structure +/- 50 to 100% relative to background
- Combined uncertainties ~100%

Tons/Km Mass at 450-1050 km in April 2016 (93% of future shrapnel

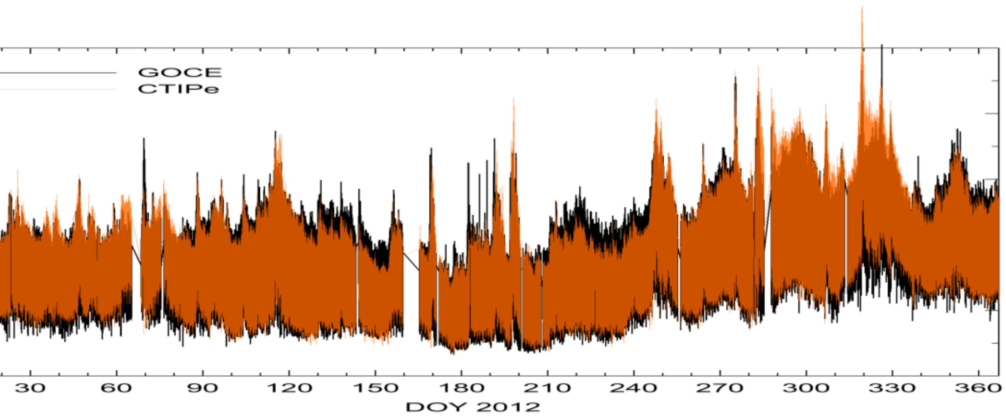


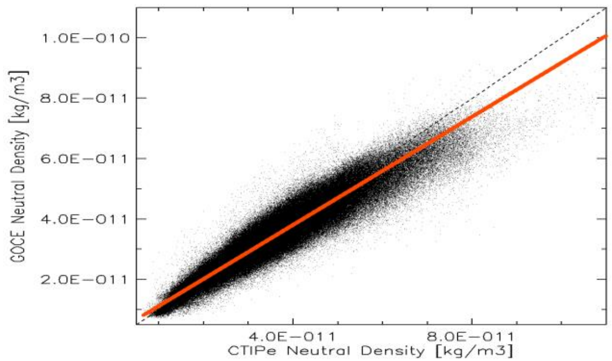
Modeling extreme events

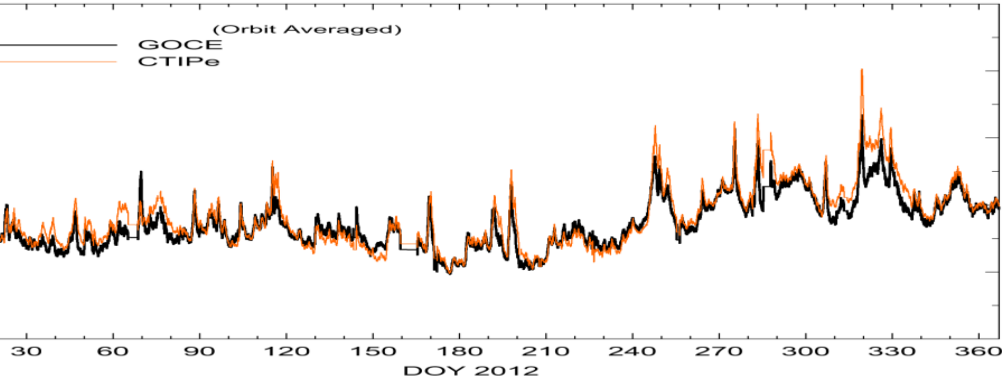


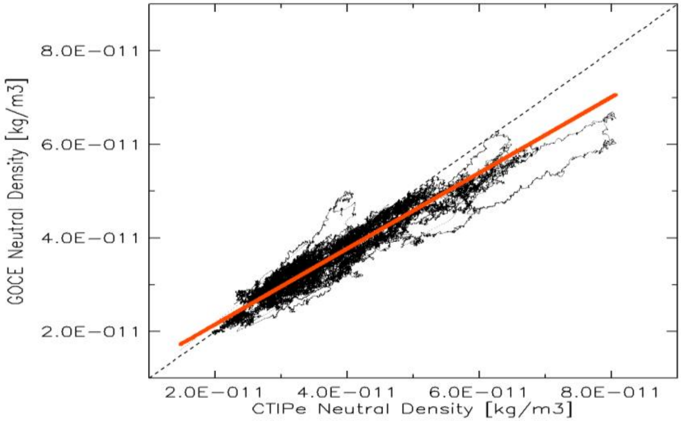
- What would be the impact of a Carrington type event on the geospace system?
- Would our thermosphere-ionosphere-magnetosphere models be about to cope?
- Do the physical processes in the model operate in the same way during an extreme event, do they become more non-linear?
- Are there new physical processes we will need to accommodate and understand?
- How do we validate extreme events?

2012 GOCE/CTIPe Comparisons: Along Orbit vs. Orbit Averaged

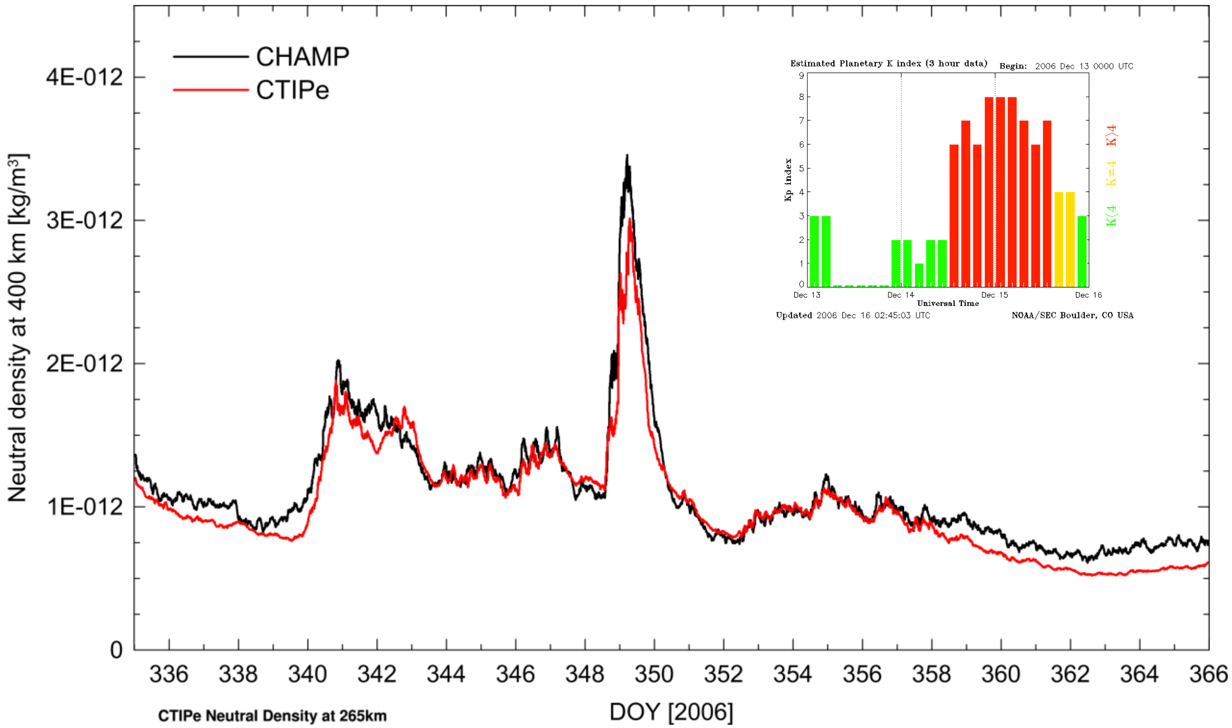


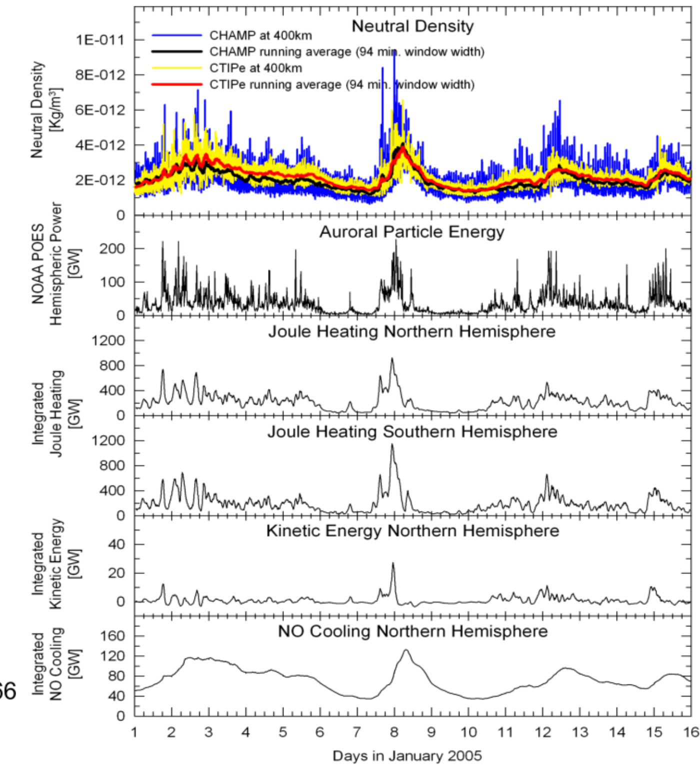


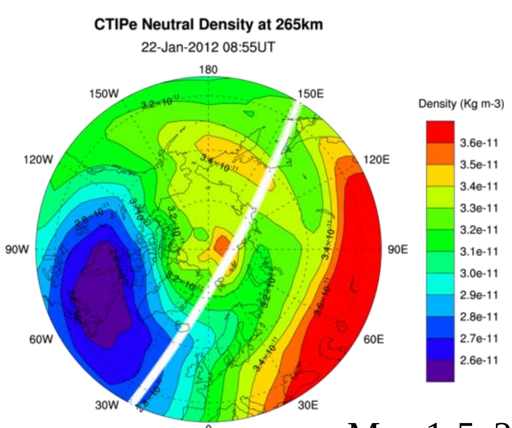




CTIPe vs CHAMP Dec 2006
Mariangel Fedrizzi





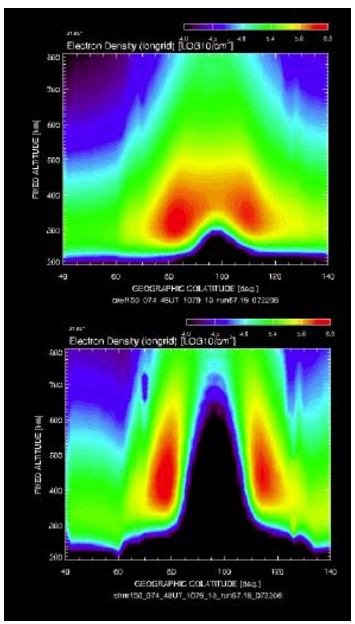


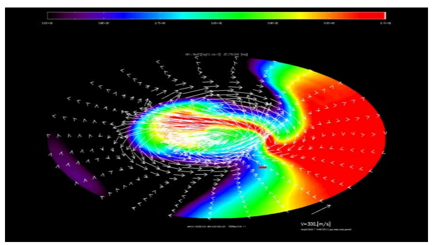
What would this density response look like during a Carrington event?

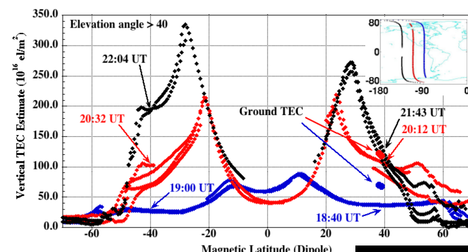
What is the magnitude of the Joule heating rates?

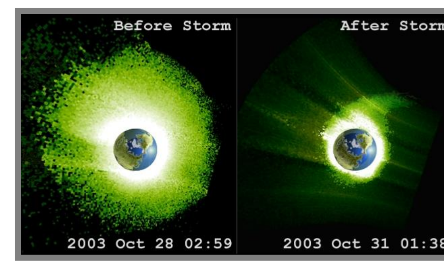
Ionospheric Storm vs Geomagnetic Storm

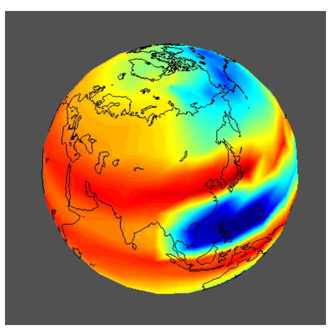
- An "ionospheric storm" are the ionospheric consequences of a "geomagnetic storm"
- Traditionally couched as "positive" and "negative" phases
- Now use terms like "storm enhanced density" and "plasma erosion"

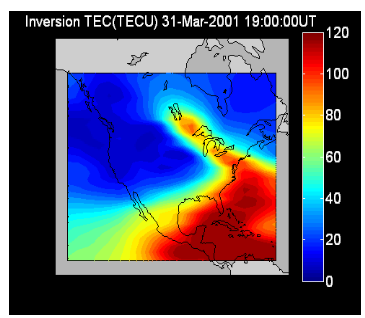


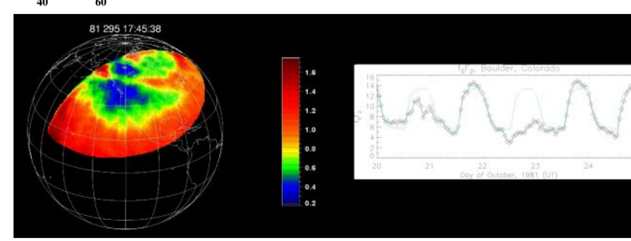


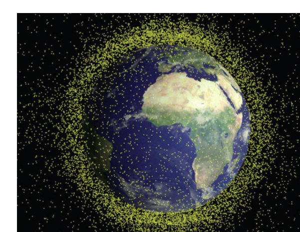




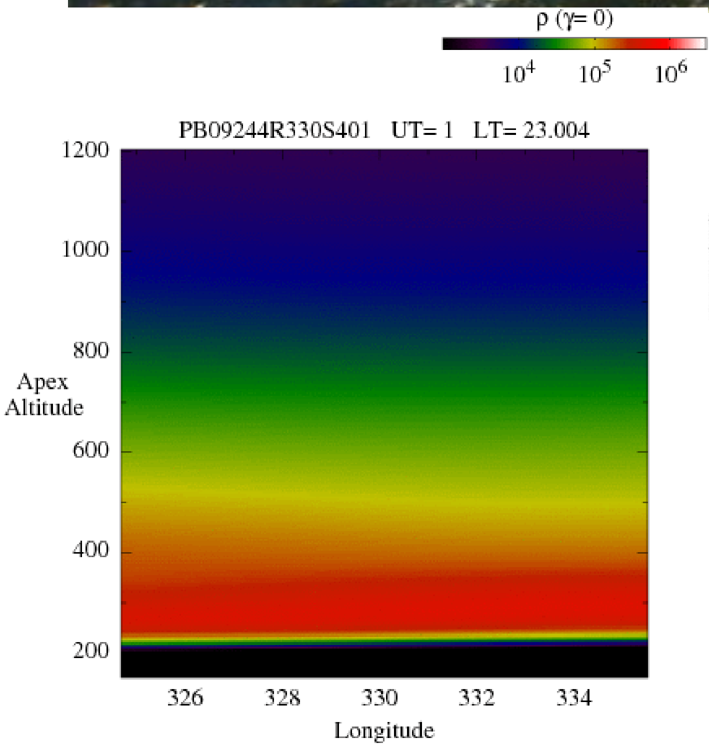


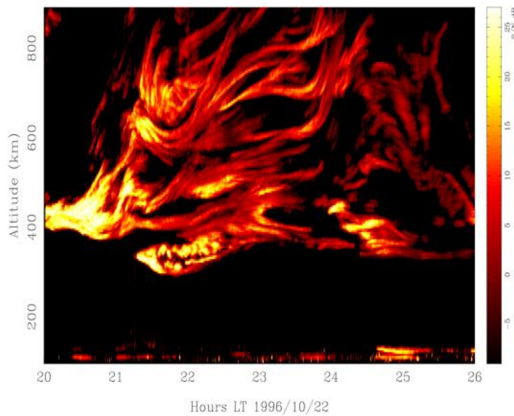


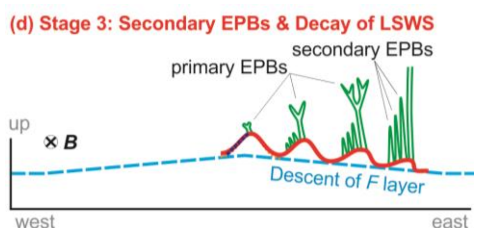


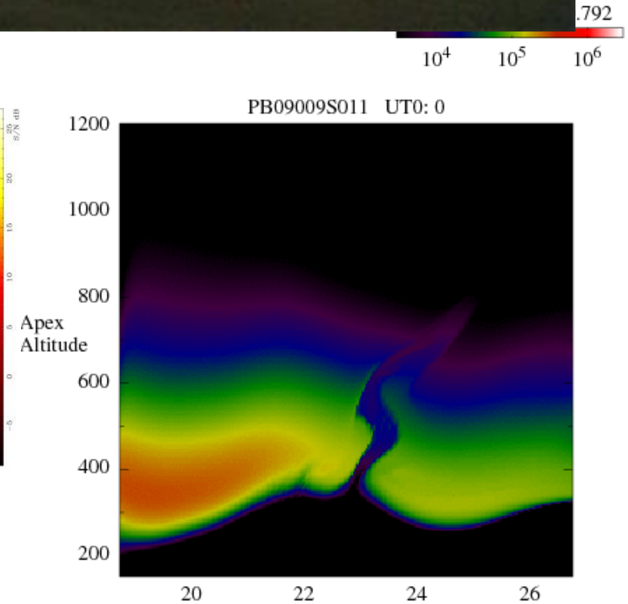


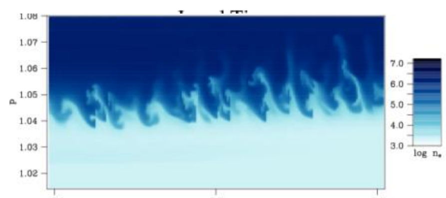
Another space weather hazard:
plasma “bubbles” or ionospheric irregularities at low latitudes

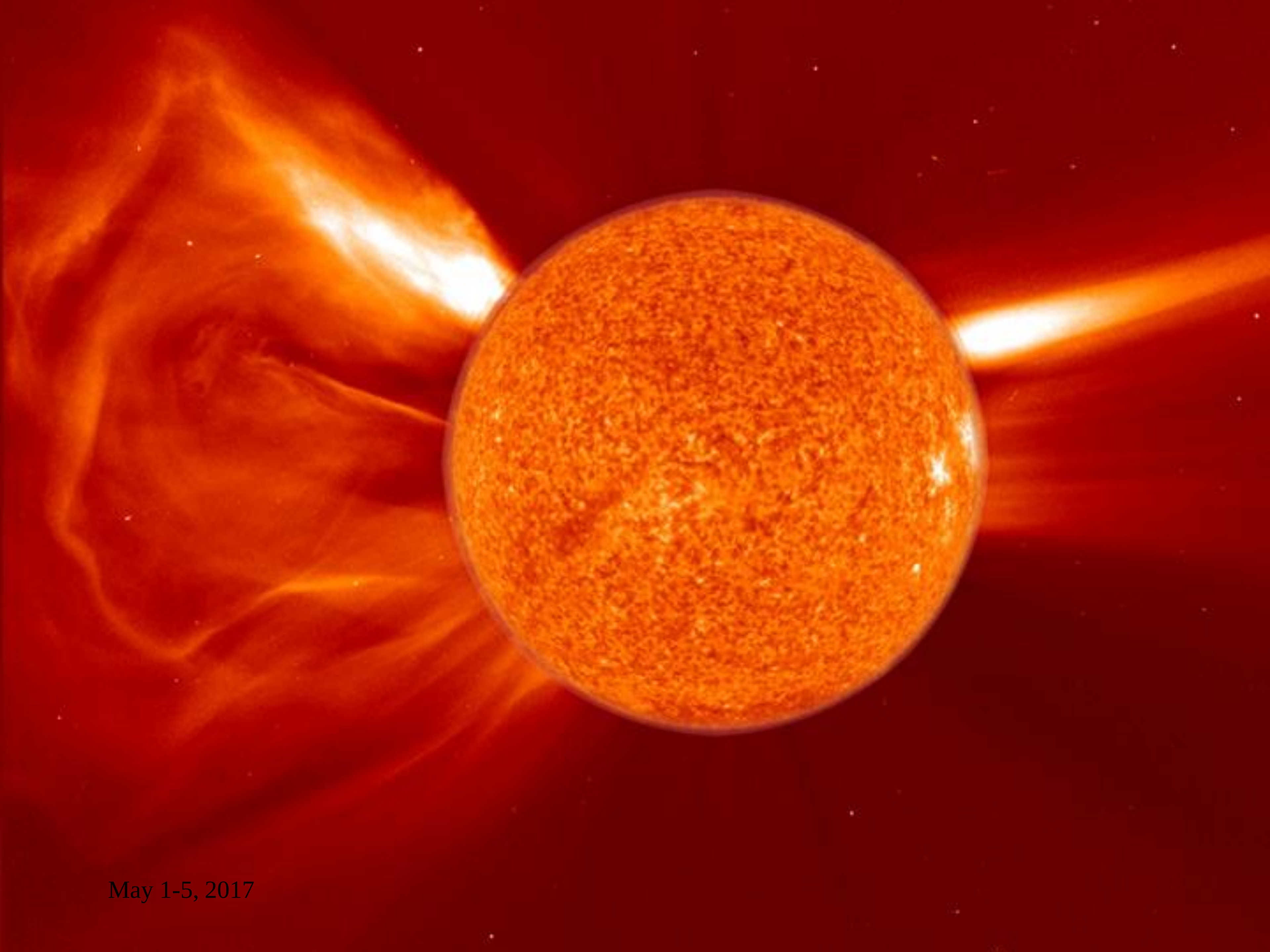












May 1-5, 2017

Modeling extreme events

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